A Thesis submitted to the Department of Environmental Sciences and Policy of Central European University in part fulfilment of the Degree of Master of Science

Technological and Psycho–Sociological Perspectives on Closing the Sanitation Loop

Nutrient Recovery and Volume Minimisation through Anion–exchange and Alkaline Dehydration of Human Urine

Psycho–Sociological Analysis of Farmer Perceptions and Attitudes on the Re–use of Human Wastes in Agriculture – The Case of Vellore, South India

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Author's declaration

No portion of the work referred to in this thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.

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ABSTRACT OF THESIS submitted by:
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To promote circularity in sanitation, this thesis examined the development of a process that could make nutrient recycling from human urine as attractive as the use of synthetic fertilisers in agriculture. Through a psycho–sociological lens, it also analysed attitudes among 120 South Indian farmers towards re–use of human excreta. The technological approach proposed here takes advantage of source–separation in urine–diverting dry toilets and integrates it sequentially with anion–exchange and alkaline dehydration processes. For stabilisation and nutrient preservation, urine was subjected to ion–exchange using a strong–base resin. A sieve–based urine drying unit was designed and operated to evaluate the nutrient recovery potential of wood ash and biochar in different protocols. The combined processes resulted in >97% water removal, >70% N retention and complete P and K recovery from urine. High drying rates suggested less than 10 kg of ash per month would be required to process the urine from an entire household in just 4.15 days; thus, every individual could be made accountable for just 21–64 kg of nutrient rich products (urine+drying media) instead of 500 kg of waste (urine) each year. The farmer surveys provided insights into factors that encourage or discourage adoption of ecological sanitation technologies. Nearly half the farmers took a positive stance towards the use of human excreta in agriculture. To initiate a positive–cascade effect and proliferate recycling practices among farmers, a conceptual approach was suggested. Combining the technological and sociological perspectives, it was demonstrated that, the toilet, a simple innovation and part of everyday life holds tremendous potential to bridge the technology–society gap and promote environmentally conscious behaviour among users.

Keywords: Sustainable sanitation; Urine drying; Circular approach; Nutrient recycling; Waste management; Attitudes and perceptions; Farmer surveys

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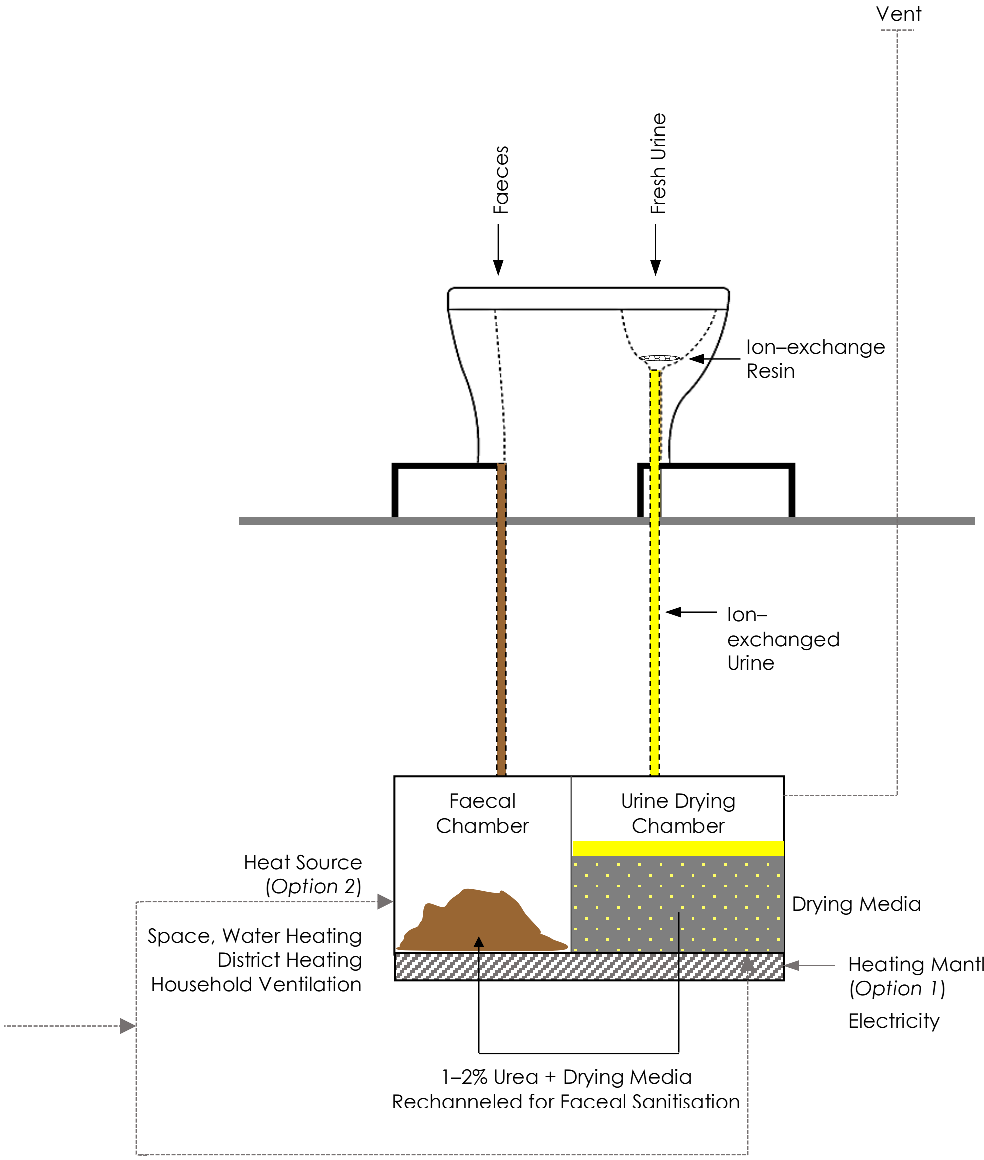
Graphical Abstract



A new approach to the design and functioning of sanitation systems

Safe nutrient recovery from human wastes by integrating anion–exchange and alkaline dehydration processes in a urine diversion dry toilet

Acknowledgements

My thesis has been more of a journey rather than a few months of work. Perhaps, it all began nearly 4 years ago with my mentor, Dr. Mahesh Ganesapillai at VIT University, India who introduced me to the concept of closed–loop technologies and ecological sanitation. Then followed my email exchanges with Dr. Håkan Jönsson (SLU, Uppsala) and Dr. Björn Vinnerås, my thesis supervisor; their work in safe nutrient recycling is what motivated me to come to Uppsala for my thesis. I am therefore thankful to the Hygiene Group (Björn, Cecilia, Annika, Jenna) at SLU for having me over, providing a wonderful and open working environment, constantly challenging my system design as well as the conceptual approach towards my thesis, and of course, tolerating me and my stream of questions. I look forward to spending the next 4–5 years with you.

I would like to thank Dr. Zoltán Illés for agreeing to supervise my thesis. Your remark, "there are *no* good choices in the environment, only *bad* and *worse*; more often than not, we have to choose between the bad and the worse" shall stay with me for a long time.

I would like to express my sincere gratitude to the ten surveyors and researchers from the Mass Transfer Group, VIT University, India for administering the farmer surveys. Indeed, we have started something beautiful in Vellore and I hope we make sure it develops over time.

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Table of Contents

List of Tables

List of Figures

Nomenclature

a_0, a_i, a_{ii}, a_{iii}, a_{ij}, a_{ijk}	:	Response Surface Methodology model coefficients for intercept, linear, squared, cubic terms and cross–product terms
di	:	Derringer's desirability function
CCRD	:	Central Composite Rotary Design
CS	:	Cannot say; farmer response
Dalits	:	Literal meaning being, *broken people*; self–designated terminology used by and referring to, so–called 'untouchable' people who traditionally occupy the lowest places in the Indian caste hierarchy. 'Scheduled Castes and Scheduled Tribes' is the official term used by Government of India to refer to Dalits; the Indian Constitution (Scheduled Castes) Order, 1950 lists 1,108 castes across 29 states in its First Schedule, and the Constitution (Scheduled Tribes) Order, 1950 lists 744 tribes across 22 states in its First Schedule
D_{eff}	:	Effective moisture diffusivity ($m^2.sec^{-1}$)
EcoSan	:	Ecological Sanitation
E_{RMS}	:	Root Mean Square Error
F		Normal Farmers (varying as F1 to F12).
GHG	:	Green House Gas
HRW	:	Human Rights Watch
IF	:	Influential Farmers (Varying as IF1 to IF3)
MAFF	:	Ministry of Agriculture, Fisheries and Food (UK)
MC_e	:	Moisture content at equilibrium (g H_2O.g dry solids^{-1})
MC_i	:	Moisture content at any time 'i' (g H_2O.g dry solids^{-1})
MC_o	:	Moisture content at time = 0 (g H_2O.g dry solids^{-1})
MR	:	Moisture Ratio
N	:	No; farmer response
N	:	Number of survey respondents
NCEUS	:	National Commission for Enterprises in the Unorganised Sector
NIMBY	:	Not–In–My–BackYard syndrome; defined by Merriam Webster as, opposition to the locating of something considered undesirable (as a prison or incinerator) in one's neighborhood
NSSO	:	National Sample Survey Organisation
OBC	:	Other Backward Class; defined by the Indian Constitution as, socially and educationally backward classes ; the Indian Ministry of Social Justice and Empowerment maintains a dynamic list of OBCs
R^2	:	Coefficient of determination

R^2_{Adj}	:	Model Adjusted coefficient of determination
RSM	:	Response Surface Methodology
RSS	:	Residual Sum of Squares
SC	:	Scheduled Caste
ST	:	Scheduled Tribe
UDT	:	Urine Diversion Toilets
WHO	:	World Health Organisation
WWTP	:	Waste Water Treatment Plant
X_i	:	Coded independent variables for RSM
Y	:	Predicted and experimental response for RSM ($L.day^{-1}.m^{-2}$)
Y	:	Yes; farmer response
α	:	Distance between center of design and factorial points in RSM
χ^2	:	Chi–square
μ	:	Mean Response

1. Introduction

For a long time, the international agenda has neglected the aspects of sanitation and health in its push for (sustainable) development. It is not surprising to note that 36% of the global population still lacks *access* to improved sanitation facilities (Cumming 2009; WHO 2013). At the other end of this spectrum lies the issue of clean drinking water with nearly 1 billion people still dependent upon unimproved sources to satisfy their daily needs (Clarke 2013). Our continued failure to address these problems has had consequences on the global health burden which have been well recognised and documented (Ashbolt 2004; Moe and Rheingans 2006; Montgomery and Elimelech 2007). While providing and improving access to sanitation is certainly a precondition for human development, the problems surrounding sanitation extend beyond its mere provisioning.

The design and operation of conventional Waste Water Treatment Plants (WWTPs) is grounded in a philosophy that considers human excreta as 'wastes' that require treatment and removal from the built environment. The primary objectives of these systems are to (i) ensure minimal exposure of humans to wastes by creating an effective barrier (toilets) and (ii) facilitate appropriate disposal of these wastes through end–of–pipe technologies (Langergraber and Muellegger 2005). When it leaves the human body, excreta although pathogenic in nature is a point source of potential disease transmission. It is through the use of a sewage network that relies upon (drinking) water to transport wastes to centralised WWTPs (Lettinga et al. 2001) that has opened up new pathways and magnified the scale of contamination beyond the 'toilet'. In addition to the linearity in flow of (waste) resources these systems promote, essential drawbacks of 'modern' WWTPs also include poor financial sustainability, high energy requirements, sensitivity to discharge loads and inadequate treatment. The ultimate disposal of the treated wastes in landfills and in water bodies only adds to the already high environmental burden (Cumming 2009; Langergraber and Muellegger 2005).

Hence, linearity, methodological reductionism and sequential uniformity appear to be characteristic attributes of the conventional approach to socio–economic development (Thelen and Smith 1996). It is precisely this cognition that also fails to consider humans (and their actions) as being part of a complex, non–linear, dynamic and interconnected system. Today, while we live in an era of high environmental consciousness we also live in times of great uncertainty of the repercussions of our past and present actions. Yet, our current systems attempt to address the problems in sanitation, health, water and agriculture in isolation. Most of our on–going efforts in these sectors are geared to seek specificity in the implemented and/or proposed solutions thereby failing to realise any synergistic benefits.

However, conceptual complexity in line with a circular systems approach and holism could be accomplished *if* agriculture (food security) is introduced into the sanitation–water–health equation. Two fundamental aspects shape the present (and future) global food security: (i) the anticipated rise in global population coupled with higher disposable household incomes in developing countries will increase the demand for quantity and quality of food; and (ii) a likely economic and physical natural resource scarcity due to limits over its extraction will constrain agricultural production. To a large extent, contemporary levels of food production have been accomplished due to the application of industrial, fossil fuel–sourced fertilisers (Vaccari 2009). However, the mobilisation of significant amounts of plant–required nutrients for fertiliser production has interfered with the functioning of global biogeochemical cycles. Cordell et al. (2009, 2011) look towards phosphorous, 90% of which is sourced for food production to depict a likely peak in its global output by 2030 and an accelerated depletion thereafter. Ensuring long–term soil fertility to sustain food production in a resource–scarce scenario undoubtedly necessitates the envisioning of approaches markedly different than those in place today. To this effect, source–separation, concentration and recirculation of human wastes (urine and faeces) from the built to the natural environment has been advocated as a sustainable solution to the issues surrounding the nexus of sanitation, water, heath, and agriculture.

1.1. Research objectives

From a technological point of view, the objective in this study is to develop a process that makes urine recycling from sanitation as attractive as the use of synthetic fertilisers in agriculture. The broader question whose answer I seek is whether we can create sanitation systems that safely recycle value–added, nutrient–rich products between urban and rural areas, in quantities that ease their application, and in forms that are plant–available.

The specific objective is to investigate the potential of anion–exchange (pre–treatment) followed by alkaline dehydration as an approach for stabilising urine and preserving its intrinsic nutrient composition. The sub–objectives here are to determine:

a. The resin dosage required for alkalinisation of urine (Section 3.1)
b. The effect of storage temperature (Section 3.1.1) and volumetric flow (Section 3.1.2) on the efficiency of anion–exchange.

A further objective in this research will be to investigate the possibility of minimising the volume of stabilised urine through passive drying operations. The sub–objectives here are to:

a. Develop a suitable system for urine dehydration (Section 3.2.2)
b. Examine the effectiveness of various drying media (Section 3.2.3 and 3.2.4)
c. Establish the nutrient recovery potential in various drying protocols (Section 3.2.6)
d. Mathematically model and optimise the drying capacity of the system (Section 3.3 and 3.4)

To provide a sociological perspective, I also examine and analyse the attitude of farmers in South India towards the use of human excreta as fertilisers (Section 3.6). An overarching goal of this analysis would be to provide insights into factors that inhibit the proliferation of human waste recycling in a socio–culturally diverse setting like India and realise where the best opportunities for immediate and/or optimum value creation lie.

1.2. An ecological sanitation approach

Ecological Sanitation (EcoSan), a concept formulated through an approach that integrates various schools of thought such as circular economy, general systems theory, industrial ecology, biomimicry and life–cycle thinking claims to address the aforementioned shortcomings in our systems and initiate a paradigm shift in the way we perceive and manage wastes (Esrey 2001; Langergraber and Muellegger 2005). EcoSan seeks to blur the comprehension of two human constructs, 'resources' and 'wastes', by contending that human excreta are in fact, resources of a natural cycle that circulates biological nutrients. It is advocated as a philosophy of handling materials that have been, until now, assumed to be wastes. EcoSan demonstrates a closed–loop methodology for reintroducing resources from wastewater into agriculture rather than letting them diffuse into fresh water systems. Since its guiding principles favour the creation of tailored, location and context–specific solutions, EcoSan does not encourage the adoption of any specific sanitation technology (Langergraber and Muellegger 2005). Before describing the design and features of EcoSan, it is necessary to characterise wastewater and depict its resource, energy and water recovery potential.

1.3. Resource potential of human 'wastes'

Considering the variations in food intake, dietary preferences, geography, socio–demography and cultural aspects, an average human being produces every day, 1–1.5 L of urine and ~140 g of faeces. Through the pioneering work of several research groups on wastewater recovery and recycling, various fractions of human wastes have been comprehensively studied and characterised (Kirchmann and Pettersson 1994; Jönsson et al.

2005; Karak and Bhattacharyya 2011; Rose et al. 2015). As illustrated in Fig. 1, every year, on an average, each person flushes away 4.5 kg of nitrogen (N), 0.5 kg of phosphorous (P), and 1.2 kg of potassium (K) in their toilets.

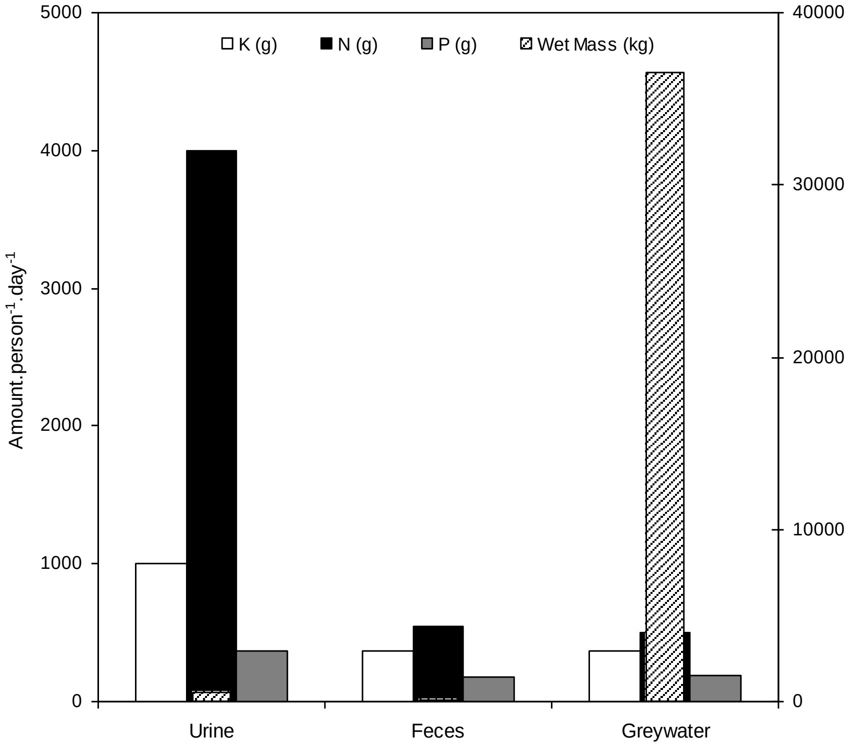


Fig. 1: Annual nutrient composition of various household waste fractions; compiled based on data sourced from Karak and Bhattacharyya (2011) and Winker et al. (2009)

Assuming that an urban setting in a developing country is made up of 10 million inhabitants, if nutrients from these wastes are recovered and recycled, the annual resource savings would amount to 45,000 tonnes of N, 5,000 tonnes of P and 12,000 tonnes of K. Furthermore, water not flushed away in the toilet would translate into annual savings of 0.15 km^3 for the same settlement.

1.4. Source separation through urine diversion

It is the above–mentioned resource potential that EcoSan, through its distinguishing feature of 'urine diversion' tries to harness (Larsen et al. 2001). The collection of urine separate from the faeces is achieved through the use of a Urine Diversion Toilet (UDT) that takes advantage of human physiology which separately excretes these fractions (Beal et al. 2008; Münch et al. 2009). A UDT is engineered to collect urine and faeces in the front end and rear–ended bowls, respectively (Fig. 2). While the predominant source of pathogens in human excreta is faecal matter, human urine is relatively sterile and contains very few pathogens on excretion (Ashbolt 2004; Jönsson et al. 2005; Beal et al. 2008). By elegantly preventing the mixing of these waste fractions, UDTs allow concentration of both nutrients as well as pathogens *at source*.

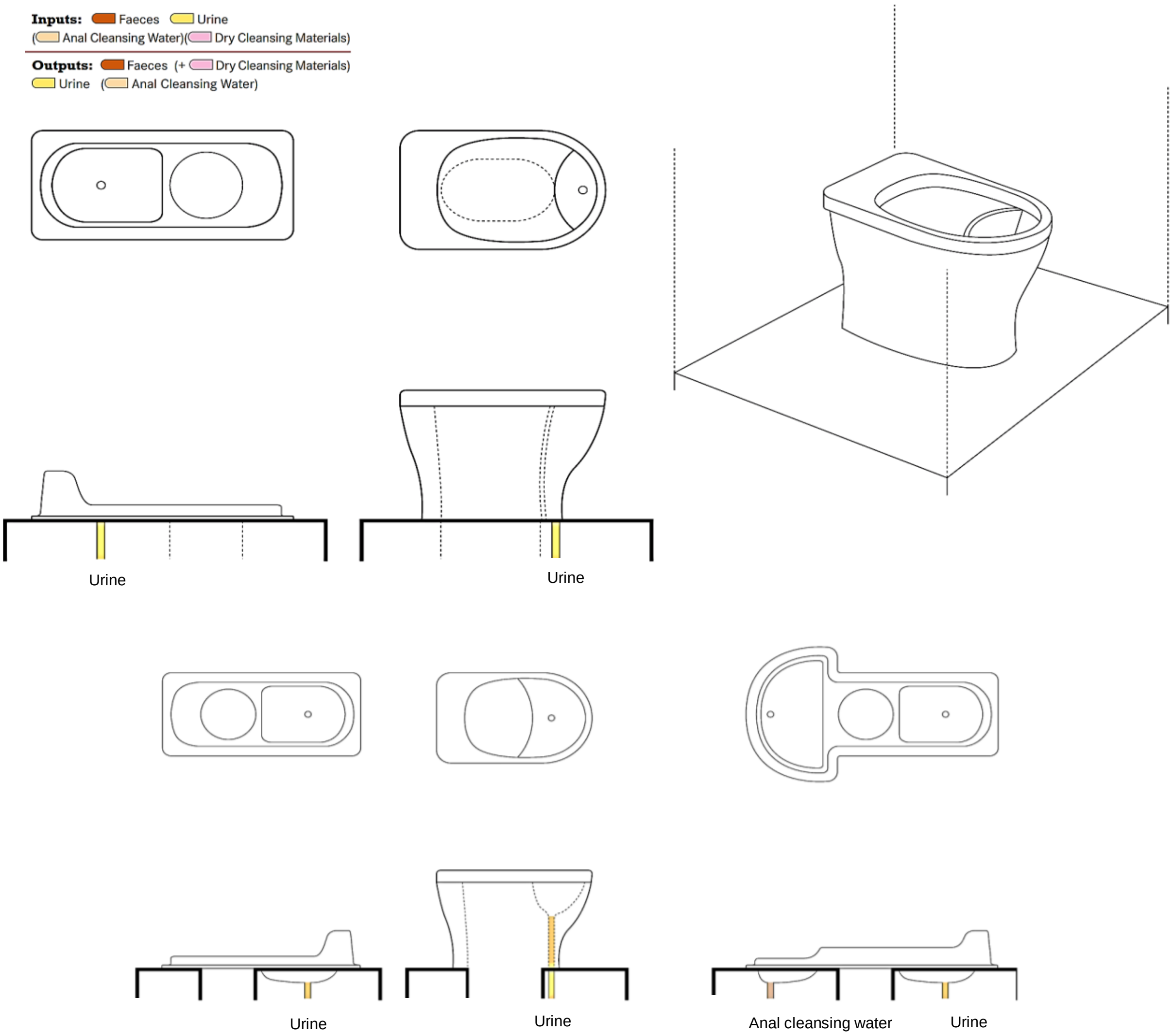


Fig. 2: The working of a typical UDT for the separation of urine and faecal fractions; Adopted from Tilley et al. (2014)

Drawing upon the concept of 'waste design' proposed by Henze (1997) source separation is in effect, a segregation step that allows better control over various process parameters that influence the efficiency of wastewater treatment. To put this into perspective, despite containing a considerably larger fraction of nutrients (80% N, 50% P and 60% K), urine makes up only 1% of the volumetric wastewater flow (Larsen et al. 2004). Wilsenach and Van Loosdrecht (2006), by modelling a process that integrates urine diversion with conventional WWTPs demonstrate that, keeping 50% of the urine from entering a conventional WWTP reduces the N–loads for treatment by ~2–3 $g.m^{-3}$; at higher rates of diversion, the WWTP could in fact achieve an energy surplus.

1.5. Adopting, implementing and validating EcoSan

Ecological sanitation attempts to close the sanitation cycle by rechannelling nutrients from human excreta to agricultural areas. The prerequisite for this recycling is the stabilisation and sanitisation of the separately collected waste fractions. To this effect, a substantial body of literature including comprehensive WHO guidelines exist (WHO 2006). Several investigations into the fertilising effect of crops using source–separated urine, compost (faeces), greywater as well as faecal sludge at different scales of implementation have been performed (Stintzing et al. 2002; Jönsson et al. 2004; Steinfeld and Wells 2004; Guzha et al. 2005; Heinonen–Tanski and van Wijk–Sijbesma 2005; Heinonen–Tanski et al. 2007; Pradhan et al. 2009).

Based on the results of these studies some broad conclusions can be drawn: (i) conditioning the soil with human excreta enhances crop productivity when compared to the control (no treatment); (ii) yields of excreta–fertilised plants are similar to that obtained when mineral fertilisers are added in the same ratio; (iii) nutrients present in excreta are either plant available or are become plant–available following their application in soil.

Since the early 1990s EcoSan and its underlying principles have been implemented as pilot projects in diverse geographical settings (Berndtsson 2006; Rosemarin et al. 2008; Tilley et al. 2009; Magid et al. 2006; Malisie et al. 2007; Bdour et al. 2009; Zurbrügg and Tilley 2009; Ronteltap et al. 2009; Werner et al. 2009). The experiences from these projects allow some further observations to be made: (i) effective adoption and/or likelihood of EcoSan adoption has been seen in industrialised countries like Germany (Steinmüller 2006), Sweden (Rosemarin et al. 2008), Netherlands (Bijleveld 2003) and Denmark (Magid et al. 2006), emerging markets like India (Langergraber and Muellegger 2005), China (Zhou et al. 2010) and South Africa (Andersson et al. 2011), N–11 countries such as the Philippines (Früh 2003), Indonesia (Malisie et al. 2007), Turkey (Bdour et al. 2009) and Pakistan (Nawab et al. 2006) as well as developing/under–developed nations including Nepal (Tilley et al., 2009), Malawi (Lungu et al. 2008), Burkina Faso (Makaya et al. 2014), Kenya (Robinson 2005), Tanzania (Shayo 2003) and Mozambique (Breslin 2002); this reiterates the underlying assumption of the geographical applicability and acceptability of EcoSan; (ii) socio–cultural attitude towards EcoSan, the use of excreta in agriculture and willingness to buy food produced using human wastes is surprisingly positive (Lienert and Larsen 2009); (iii) low capital investments, ease of infrastructural retrofitting, enhanced crop yields, the promise of an essentially 'free' and sustainable supply of nutrients and simultaneous improvement of sanitary hygiene makes urine diversion and EcoSan an exciting venture.

1.6. EcoSan, UDTs and associated problems

Although appearing ecologically–sound, the urine diversion and reuse that EcoSan advocates does exhibit some inherent flaws. At the outset, it is important to acknowledge that liquid urine is a fast acting fertiliser. Its application results in volatilisation of intrinsic ammonia (a GHG), increases soil conductivity, salinity and pH all of which could cause poor agro–productivity or as seen in some instances, crop failure (Villa–Castorena et al. 2003;

Heinonen–Tanski and van Wijk–Sijbesma 2005; Heinonen–Tanski et al. 2007). Life cycle cross–comparisons with conventional WWTPs (Jönsson 2002; Tidåker et al. 2007a; Tidåker et al. 2007b) also indicate that large volumes of urine will be required to provide a fertilising effect equivalent to synthetic crop fertilisers. This not only reduces systemic efficiency but also necessitates additional investment for its collection, storage and transportation to farmlands. Besides, as Jewitt (2011) observes, an obvious aspect hindering the spread of EcoSan and its technologies is the socio–cultural conceptualisation over the use of excrement in food production. Disregarding this for the purpose of the present analysis, more fundamental concerns can be seen in the system design itself.

UDTs are connected to urine storage tanks that have installed capacities of 300–500 L. During storage, bacterial urease (urea amidohydrolase) catalyses hydrolysis of the principal N compound (urea) as seen in Eq. 1.

$$NH_2(CO)NH_2 + 2H_2O \rightarrow NH_3 + NH_4^+ + HCO_3^- \quad (1)$$

The implications of ureolysis are three–fold: (i) it completely hydrolyses urea into ammonia that subsequently volatilises due to its low solubility during storage, elevates the pH, and reduces the potential reusability of N in post–storage applications; (ii) elevated pH triggers the precipitation of struvite ($Ca_{10}(PO_4)_6(OH)_2$) and calcite ($CaCO_3$) which creates blockages in the odour traps and pipelines (Udert et al. 2003a); (iii) it results in the physico–chemical and microbial stratification of the urine during storage (Höglund et al. 2000).

A further concern in UDTs is cross–faecal contamination of the relative sterile and source–separated urine. Inactivation studies with urine point towards significant pathogenic risk over its use due to the persistence of, among others, faecal sterols, *Escherichia Coli*, *Salmonella* Typhimurium, *Ascaris suum* eggs and *rhesus* rotavirus (Sundin et al. 1999; Höglund et al. 2002a; Nyberg et al. 2014; Winker et al. 2009). In a study that analysed 15 different storage tanks in Sweden and Australia, faecal sterols were found to cross–contaminate 22% of the samples in the upper portion and 37% of the samples from the sludge (Schönning et al. 2002). Nyberg et al. (2014) argue that microbial persistence also extends to the application of excreta in soils which creates further disease transmission pathways.

Given these factors, WHO recommends that urine be stored in tanks for a period of 6 months to achieve adequate sanitisation. Storage without any pre–treatment (stabilisation), however, would lead to the above–mentioned problems of ureolysis. Moreover, the quantification, behaviour and potential effects of micro–pollutants such as pharmaceutical residues in source–separated human urine are not well understood. In light of this scientific uncertainty, Larsen et al. (2004) invoke the precautionary principle over the application of fertiliser products from sanitation systems.

The narrative adopted here elucidates the design flaws in EcoSan systems that have stalled the proliferation of nutrient recycling. Certainly, EcoSan does provide an efficient way to separate, collect and concentrate products that we require (nutrients) and those that we wish to regulate (pathogens, micropollutants, heavy metals). However, it is in the subsequent steps of envisioning and implementing appropriate processes for recovering and reusing nutrients following their source separation that provide opportunities for substantial value creation as well risk minimization. This follows the corollary of the end goal a sustainability–centric sanitation system wishes to achieve. In effect, what we seek in the end are value added, nutrient–rich products in quantities that ease their handling and application, in forms that make them readily available to plants while being relatively free from pathogens and micro–pollutants.

Fig. 3: Schematic representation of the literature analysis for EcoSan and sustainable sanitation

The Rationale for Sustainable Sanitation

Ashbolt, 2004; Clarke, 2013; Cordell et al., 2009; Cordell et al., 2011; Cumming, 2009; Godfray et al., 2010; Guest et al., 2009; Langergraber and Muellegger, 2005; Moe et al., 2006; Montgomery and Elimelech, 2007; Smit et al., 2009; Vaccari, 2009

Ecological Sanitation: Origins and Concepts

Beal et al., 2008; Berndtsson, 2006; Esrey, 2001; Haq and Cambridge, 2012; Henze, 1997; Jewitt, 2011; Johansson and Kvarnström, 2005; Katukiza et al., 2012; Langergraber and Muellegger, 2005; Larsen et al., 2001; Rosemarin et al., 2008; Münch et al., 2009; Vinnerås and Jönsson, 2002a; Vinnerås and Jönsson, 2002b; Werner et al., 2009

Resource Potential of Human Wastes

Boller, 2007; Jönsson et al., 2005; Karak and Bhattacharyya, 2011; Kirchmann and Pettersson, 1994; Meinzinger and Oldenburg, 2008; Rose et al., 2015; Sullivan and Grantham, 1982; Tettenborn et al., 2007; Wendland, 2008; Winker et al., 2009

Agronomic Validation of Source–Separated Wastes

Guzha et al., 2005; Heinonen–Tanski et al., 2005; Heinonen–Tanski et al., 2007; Jönsson et al., 2004; Karak and Bhattacharyya, 2011; Pradhan et al., 2009; Pronk and Koné, 2009; Richert Stintzing et al., 2002; Steinfeld and Wells, 2004

Implementing EcoSan: Experiences

Andersson et al., 2011; Bdour et al., 2009; Berndtsson, 2006; Bijleveld, 2003; Breslin, 2002; Etter et al., 2011; Früh, 2003; Johansson and Kvarnström, 2005; Larsen et al., 2001; Lienert and Larsen, 2009; Lixia et al., 2007; Lungu et al., 2008; Magid et al., 2006; Makaya et al., 2014; Malisie et al., 2007; Nawab et al., 2006; Otterpohl et al., 1997; Rajbhandari, 2008; Robinson, 2005; Ronteltap et al., 2009; Rosemarin et al., 2008; Shayo, 2003; Steinmüller, 2006; Tilley et al., 2009; Werner, 2001; Werner et al., 2009; Zhou et al., 2010; Zurbrügg and Tilley, 2009

Resource Recovery from Human Wastes: Technologies

Dalahmeh et al., 2012; Dalahmeh et al., 2014; Dodd et al., 2008; Etter et al., 2011; Ganesapillai et al., 2015; Ganrot et al., 2007; Katukiza et al., 2012; Kujawa–Roeleveld and Zeeman, 2006; Larsen et al., 2004; Lind et al., 2000; Maurer et al., 2006; O'Neal and Boyer, 2013; Pillai et al., 2014; Pronk et al., 2006; Ronteltap et al., 2007a; Ronteltap et al., 2007b; Sakthivel et al., 2012; Simha, 2014; Tilley et al., 2009; Udert and Wächter, 2012; Uysal et al., 2010; Wilsenach et al., 2007; Zhang et al., 2014; Zhigang et al., 2008

Problems

Decrey et al., 2011; Höglund et al., 2000; Höglund et al., 2002a; Höglund et al., 2002b; Jewitt, 2011; Larsen et al., 2004; Makaya et al., 2014; Nyberg et al., 2014; Pronk and Koné, 2009; Ronteltap et al., 2007; Schönning et al., 2002; Sundin et al., 1999; Udert et al., 2003a; Udert et al. 2003b

Potential Solutions

Dalahmeh et al., 2012; Elving et al., 2014; Fidjeland et al., 2013; Lalander et al., 2013; Magri et al., 2013; Magri et al., 2015; Nordin et al., 2009; Pronk et al., 2006; Vinnerås et al., 2003a; Vinnerås et al., 2003b; Vinnerås et al., 2008; Winker et al., 2009

Closed–Loop Sanitation

Sanitation–Health–Water–Food Nexus

1.7. Technologies for nutrient recovery: progress, gaps and opportunities

Since EcoSan considers technologies as an end–point in closing the loop on sanitation, it does not favour any particular technological solution. While it is understood that sanitation systems need to be tailored to suit local conditions, it would seem from the above narrative that, in fact, the realisation of an appropriate technological solution(s) that satisfies the aforementioned requirements is vital to achieving circularity in sanitation. To this effect, recent research efforts have been devoted towards the development of technologies that can safely harness nutrients from human excreta to yield usable end–products (Kujawa–Roeleveld and Zeeman 2006; Maurer et al. 2006; Pronk et al. 2006; Ganrot et al. 2007; Dodd et al. 2008; Udert and Wächter 2012; O'Neal and Boyer 2013; Dalahmeh et al. 2014; Zhang et al. 2014; Ganesapillai et al. 2015) (Fig. 3).

An approach favoured by many researchers has been struvite ($Mg{\cdot}NH_4{\cdot}PO_4.6H_2O$) precipitation where significant P and an appreciable amount of N as precipitated $(NH_4)^+$ has been recovered (Udert et al. 2003a; Ganrot et al. 2007; Ronteltap et al. 2007; Wilsenach et al. 2007). As mentioned before, ureolysis during the storage of urine increases the solution pH. This, in turn, reduces the solubility of $(PO_4)^{3-}$ which combines with all the intrinsic Mg^{2+} in urine to induce supersaturation and spontaneous precipitation within the storage tank. However, to increase the recoverability of P and N as struvite, urine has to be supplemented with external addition of Mg as MgO, $MgSO_4{\cdot}7H_2O$ or $MgCl_2{\cdot}6H_2O$.

Other advocated technologies that demonstrate considerable recovery have been physical filtration (Dalahmeh et al. 2014), ozonation (Dodd et al. 2008), anaerobic treatment (Kujawa–Roeleveld and Zeeman 2006), adsorption/biosorption (Ganesapillai et al. 2015), nitrification–distillation (Udert and Wächter 2012) and forward osmosis (Zhang et al. 2014). Through the analysis of this body of literature on nutrient cycling, the following constructive criticism as well as some observations can be made. The purpose of this analysis is not only to depict technological shortcomings but more importantly, to understand the salient aspects that influence the design of an integrated sanitation system.

a) Although these technologies have been influenced by ecological considerations, they demonstrate variable efficiency in recovery of the major excreta nutrients (N, P and K)

b) Several among these processes have been engineered to optimise certain parameters thereby failing to provide an integrated solution. In their review of existing technologies, Maurer et al. (2006, p. 3154) reiterate this observation. For instance, N removal through struvite precipitation is relatively poor in comparison to the recovered P (Lind et al. 2000). Further, pathogen build–up and persistence has been recognised in the precipitated struvite in spite of post–separation air drying of the cake (Decrey et al. 2011). Also, by controlling the dosage of $MgCl_2 \cdot 6H_2O$ and the pH of urine, it is possible to precipitate either potassium magnesium phosphate (KMP) or magnesium ammonium phosphate (MAP). Complete P recovery can be attained by the precipitating either of these compounds. (Wilsenach et al. 2007).

c) Certain processes show promise in terms of their recovery potential but require large capital infrastructure or entail high operating costs (Pronk et al. 2006; Udert and Wächter 2012)

d) The concentration of heavy metals in the waste fractions is well within the regulatory requirements for fertiliser application and requires no further treatment. Moreover, a significant finding during experiments with struvite shows that hormones and pharmaceutical residues remain within the solution separate from the target P compound. (Ronteltap et al. 2007b)

e) In order to improve the process feasibility and ensure its competitiveness against conventional fertiliser production, a simultaneous reduction in sanitisation time for pathogen inactivation along with their complete removal is necessary to meet regulations. The current time frame of 6 months as stipulated by WHO results in complete sanitisation but reduces system efficiency (ureolysis; Eq.1).

f) Solution pH, storage temperature and dilution via flush water strongly influence the following factors: (i) solubility and speciation of various components which determines their precipitation dynamics as well as the quantity and form of recoverable nutrients; (ii) the effectiveness and time required for pathogenic inactivation (Vinnerås et al. 2008).

g) Urea is a plant–available nutrient and the most abundant component in human urine. It is also one of the most widely manufactured mineral fertilisers. Therefore, it is surprising to note the lack of research effort devoted to finding pathways for its un–speciated post–storage recovery.

1.8. Towards closing the loop on sanitation

Recent studies indicate that the time required for sanitisation can be significantly reduced vis–à–vis those stipulated by WHO by elevating the pH (and temperature) of source separated urine to ≥ 10.5 (Winker et al. 2009; Randall et al. 2016). The enzymatic hydrolysis of urea by urease is strongly dependent on the solution pH. Sissons et al. (1990) reported that urease activity falls to less than 10% of its maximum activity around the pH of 9. Therefore, *alkalinisation* represents an elegant and effective approach to stabilise and preserve the nutrient composition of urine.

Ion–exchange processes have been known to provide selective removal/recovery of compounds from polluted water and wastewater (Milmile et al. 2011; Hekmatzadeh et al. 2012; Landry et al. 2013). Human urine contains several anions whose strength varies as: $HCO_3^{1-} < Cl^- < NO_3^- < PO_4^{3-} < SO_4^{2-}$ (Putnam 1971). Further, the concentration of Cl^- as

NaCl is relatively larger than the rest and can potentially be rapidly exchanged with hydroxide (OH^-) ions thereby, simultaneously elevating the pH of urine to levels required for stabilisation (≥ 10.5). Although the concentration of anions in urine varies, an average theoretical exchange capacity of urine reported in literature is 0.22 $eq.L^{-1}$ (Hagardorn et al. 2001). Hence, an objective of this study will be to evaluate the stabilisation potential of strongly basic anion–exchange resins towards inhibition of ureolysis and nutrient preservation. Elevation of pH will be performed by using an Amberlite™ IRA410 type–2 resin that selectively replaces anions in urine with OH^-.

A further objective in the study will be to realise *volume minimisation* of ion–exchanged and stabilised urine through passive drying operations. A significant factor constraining the proliferation and adoption of human waste recycling is the large quantities of urine that needs to be handled, stabilised, transported and ultimately, re–applied on arable land as liquid fertiliser. This poses considerable financial burden on the system that requires both retrofitting as well as well as expenditure on new equipment (urine diversion toilets, storage tanks, pipelines, etc.) in addition to being very challenging to manage logistically.

Here it is pertinent to reiterate that current systems as well as conventional wisdom perceives human excreta as 'wastes' thereby justifying its treatment and disposal. If that is the case, it is surprising to note that volume minimisation is *not* an objective in current waste treatment operations. On the contrary, 'modern' sanitation system utilise (drinking) water to mediate the transport of these 'wastes' magnifying not only the scale of probable likelihood of disease transmission but also, the volumes of waste that require processing and treatment at the end–of–the–pipes.

Hence, in the present study, ion–exchanged urine will be subjected to passive drying operations (≤ 50°C) with three sub–objectives: (i) to ensure minimal thermal degradation of nutrients in urine to maximise their recovery; (ii) to minimise the volume of the urine by removing ≥ 90% of its water content; and (iii) to optimise the drying process (using Response Surface Methodology) to ensure minimum drying times (and energy input) and/or maximum rates of urine drying. It is important to note that water makes up 97% of the total volume in human urine and that, urine is one of the most conductive biological fluids (0.56 $W.m^{-1}.K^{-1}$) (Poppendiek et al. 1967). Therefore, for urine dehydration, a suitable drying system will be designed and built to investigate the performance and effectiveness of two drying media, wood ash and biochar. The rationale behind spreading the urine over a drying media is to provide high surface area for moisture removal as well as to breakdown urine peptide films which would otherwise be formed during dehydration.

Burning of wood offers a locally available and cheap source of energy and heat. It finds popular use in district and domestic heating and is considered a renewable energy source due to its carbon neutrality (Werkelin et al. 2005). Due to these attributes as well as growing environmental pressures to meet decarbonisation and renewable energy targets, woody biomass burning for energy/heat generation has seen tremendous increase over the years. In particular, wood fuels account for 22% (377 TWh) of the total final energy use in Sweden (Swedish Forest Agency 2013). Alternatively, biomass burning is a common practice followed by half of the world's population and is a primary source of energy and heat for cooking, lighting and heating in developing and underdeveloped countries (Ludwig et al. 2003). Ash is an undesirable waste product from the burning of wood and biomass. However, it does contain appreciable concentrations of plant–required nutrients and more importantly, is highly alkaline in nature (Hytönen 2003). Given these favourable characteristics, wood ash has potential to be a good media for urine drying.

On the other hand, biochar, a highly carbonaceous charred organic material has been deliberately applied as a soil conditioner with the intent of improving soil quality and associated environmental services (Lehmann et al. 2006). Several studies have pointed out that the application of biochar for soil conditioning and amendment is a 'multiple–win' strategy (Jeffery et al. 2015) with its most touted benefits being carbon sequestration, waste disposal, enhanced plant nutrient uptake, pollutant immobilisation and simultaneous biofuel production (Sohi et al. 2010). Investigations on the agronomic value of biochar also point toward the possibility of increasing crop yields through soil conditioning (Chan et al. 2008; Liu et al. 2012; Kumar et al. 2013). However, the increase in crop productivity in these studies was due to the combined interactive effect of biochar and an externally added N fertiliser. For instance, Chan et al. (2008) observed that there was no significant effect of biochar addition on productivity in the absence of N fertilisers. The same authors also demonstrated a corresponding increase in productivity as biochar addition was increased in the presence of N. Similar observations on the inherent dependency of biochar on external fertiliser additions for augmenting crop growth have been made by Van Zwieten et al. (2012) in their studies on wheat and radish biomass yields. Therefore, similar to wood ash, biochar could also be potentially used as a drying media for human urine. Besides, combing the nutritive effect of human urine with the soil conditioning effect of biochar offers an exciting possibility for creating further value addition.

1.9. Psycho–sociological analysis of Indian farmer attitudes

Undeniably, technology and innovation have had far–reaching implications on, among others, societal functions, human behaviour, cultural practices, policy formulations and governance, economies, markets, and the environment. Over time, our heuristics of past technological transitions and conceptualisation of approaches that guide sustainable innovations have evolved considerably. We now recognise these shifts that technologies initiate as Socio–Technical Transitions (STTs), emphasising their embedment within wider socio–economic systems (Rip and Kemp 1998). However, in most if not all transitions, the strategic positioning of stakeholders against a proposed technology features strongly in determining its adoption and influences the timing, extent, swiftness and magnitude of its diffusion (Geels 2002). In the case of EcoSan two such key stakeholders are;

a. *Consumers* – stakeholders that need to be motivated to shift from flush–and–forget toilets (which they have been accustomed to) to using urine–diverting toilets. Consumers are vital since the initiation of a closed–loop sanitation cycle through source–separation begins in households.

b. *Producers* – stakeholders among whom, interest, motivation and acceptance of source–separated human wastes as a fertiliser must be created, developed and sustained over time.

The consumers and the producers represent both, the sources as well as the sinks for nutrients in an ecological sanitation cycle. Here, nutrient mobilisation begins through consumers in their households (source) where source–separation provides an avenue to direct them to agricultural areas (sink). On farms, the cultivators immobilise these nutrients during crop fertilisation and production (source) through which nutrients ultimately end up as food for consumers (sink).

However, relatively less research attention and effort has been devoted towards recording farmer perceptions, attitudes, and willingness to transition towards the use of these alternative fertilisers. In a very recent review on the subject, Leinert (2013) points towards the dearth of sociological research in urine recycling. She remarks, '*I know of four questionnaire surveys addressed to the general public and four to the farmers that elicited their acceptance of reusing human urine in agriculture*' (Chapter 14, p. 202). These studies and those published following Leinert's review seek to provide a socio–technological perspective on consumer attitudes over the design and use of urine–diverting toilets. These include Pahl–Wostl et al. (2003; Switzerland), Cordova and Knuth (2005; Mexico), Lienert and Larsen (2006; Switzerland), Lienert and Larsen (2009; EU Review), Lamichhane and Babcock (2013;

Hawaii), Mugivhisa and Olowoyo (2015; South Africa), and Ishii and Boyer (2016; USA). The few surveys there are on farmer attitudes were carried out in Ghana (Mariwah and Drangert 2011) and Switzerland (Leinert et al. 2013). To the best of my knowledge, no psycho–sociological research over *farmer* attitudes on the subject has been performed in India. Here, I do not take into consideration the survey by Rahman and Chariar (2015) as their investigation dealt only with region–wise level of acceptance/willingness of Indian farmers without delving into the reasons for the existence of such attitudes. Hence, this study will also provide a psycho–sociological and cultural analysis of South Indian farmers to understand the factors that encourage/discourage, negative and positive attitudes towards human waste recycling.

1.10. Scope and limitations

Although the broader objective is to demonstrate the resource potential of human wastes and to find a suitable approach to harness it, my focus in this study is entirely devoted to urine recycling. No experiments were performed with respect to the faecal fraction of urine diverting toilets. Nonetheless, approaches for faecal recycling based on previous studies have been recommended. Moreover, I also depict how the recycling of both these fractions can be accomplished within a single, self–functioning and self–operating toilet.

As a potential nutrient recovery process this study looks towards the combination of anion–exchange (as a pre–treatment) and urine drying over a media. While experiments on human urine were performed separately for these two steps, in effect, it is the combination of the two that must be perceived as being part of the design of an entirely new toilet that this study attempts to put forward (See Section 3.5; p. 77).

With respect to the second half of this study which analysed the perceptions and attitudes of Indian farmers towards human waste recycling, any observations and conclusions drawn are strictly representative of the geographical extent of the surveys (District of Vellore, TN, India). The survey and its conclusions must therefore not be considered a general representation of Indian farmer attitudes on the subject. Furthermore, any reference to a particular social group, religion, caste, or other classifications has been done strictly for the purposes of academic research without any ulterior motive whatsoever. Any inferences drawn from the responses of a particular group have been used only to gain insights into perceptions, behaviour, and attitudes towards waste recycling.

2. Methods and materials

2.1. Urine and anion–exchange

Fresh human urine was collected from volunteers at Sveriges lantbruksuniversitet, Uppsala, Sweden in 1 L polypropylene containers. 1% of the urine from each obtained sample was refrigerated at –20°C to determine its initial properties. In order to inhibit urea–N hydrolysis and allow nutrient preservation within the solution, pH of the urine was elevated through anion exchange. Industrial grade Amberlite™ IRA410 type–2 resin (Merck Chemicals GmbH, Darmstadt, Germany) was utilised as spherical beads (harmonic mean diameter of 0.60–0.75 mm)* of styrene divinylbenzene copolymer with dimethyl ethanol ammonium ($R–N^{+}(C_2H_5)_2(C_2H_5OH)$) functional group. The resin was used in the chloride form and has an exchange capacity* of 1.25 $eq.L^{-1}$.

Initially, the effect of resin dosage on the urine pH was examined by mixing 500 mL urine with the resin (5–35%, v/v) at shaker speed of 175 rpm and room temperature (20 ± 0.5°C) for 5 min. Subsequently, a resin to urine ratio of 0.2 or 20% resin loading was identified as being sufficient to necessitate the required pH elevation.

The effect of temperature on the anion–exchange was studied at room temperature (20°C), 37°C and 50°C. Three Erlenmeyer flasks (500 mL) with 250 mL of anion–exchanged urine (resin dosage of 20% v/v) were covered with aluminium foil and kept in three incubators (Electrolux, Sweden) at the above mentioned temperatures. The pH of the flasks was monitored over time; further, 3 mL aliquots were withdrawn at different time intervals and analysed for change in total–N and NH_4–N.

In order to determine the effect of urine diversion and interaction with the resin, fresh urine samples (500 mL) were divided into five equal 100 mL fractions. Each fraction was then

* Data available from manufacturer

sequentially mixed with 100 mL of the resin in Erlenmeyer flasks (250 mL) for 1–2 min over a magnetic stirrer. For fraction 1, 20 mL urine was passed through the resin and mixed with 80 mL un–diverted (fresh) urine; similarly, 40, 60, 80 and 100 mL urine was subjected to anion exchange and mixed with 60, 40, 20 and 0 mL fresh urine to represent fractions 2, 3, 4 and 5 respectively. The resin was dosed by volume measured in graduated cylinders. To ensure representativeness and account for variability in nutrient composition of urine due to different dietary preferences (Putnam 1971; Kirchmann and Pettersson 1994), 50 different urine samples were considered and anion–exchange was performed for each as per the procedure mentioned above.

Following each experimental run, the resin was regenerated with 250 mL of 3% (w/w) KOH solution in a shaker at 175 rpm for 1 h. Subsequently, the resin was washed with distilled water until the pH of the wash water was *ca.* 9. Additionally, to remove any unfiltered struvite precipitating over the resin, acid wash with 0.1 M H_2SO_4 followed by rinsing with distilled water was carried out after every five ion–exchange runs.

2.2. Drying media

Ash was collected from residential households in Uppsala that utilised birch wood sourced from central Sweden for domestic heating. The collected ash was sieved (< Ø 1 mm) and larger particles were discarded. Since the burning of wood results in the breakdown of its major constituents (hemicellulose, cellulose and lignin) into various organics such as acetic acid, formic acid, lactic acid, levoglucosan, phenols, etc. (Sjöström 1993), it was subjected to thermal pre–treatment for removal of volatiles and moisture at 500°C for 5 h in a furnace (LH30/12, Nabertherm GmbH, Germany). Subsequently, it was allowed to reach room temperature and stored in air–tight containers until further use. The biochar was manufactured through pyrolysis (450°C) of chopped willow trees (Salix) grown in Germany and were sieved to < Ø 1 mm before use. To increase the pH of the biochar to ≥12.5, KOH pellets were added to the biochar in a weight ratio of 1:4 (Tseng and Tseng 2005). The KOH was dissolved using deionised water and kept aside for 1 h to ensure uniform dissolution. Following this, the mixture was oven–dried overnight at 110°C and the biochar obtained was used in further experiments. Characterisation studies were performed for the wood ash and biochar to determine their initial properties – density, pH, ash content and concentrations of total–N, P and K.

2.3. Drying setup

The schematic diagram for the ash/urine drying system is provided in Fig. 4. Drying was carried out by modifying a conventional benchtop incubator (Electrolux, Sweden) with inbuilt cavity of 470 × 330 × 580 mm and adjustable temperature setting ranging from 30–60°C. Two circulating fans (CF1 and CF2) were installed to allow uniform heat distribution in the cavity. An air pump (P1) was introduced into the system to remove the moisture laden air from the drying chamber. The pump was connected to an air flow meter (FM1) and a gate valve (V1) to regulate the air suction flow rate from the system. Pre–treated wood ash and biochar (1 < Ø < 0.25 mm) were spread uniformly over a 250 µm sieve (inner Ø: 0.198 m; surface area: 0.0308 m^2) and gently shaken to ensure they do not pass through it. The sieve was then placed at the centre of the drying chamber. Temperature was measured using three SS 304 probes with DS18B20 1–Wire temperature sensors (OW–TEMP–B3–12xA, Embedded Data Systems LLC, USA). The probes measure temperature in the range between –55 and 125°C with an accuracy of ± 0.5°C; S1 was installed at 25 mm distance above the sieve, S2 was installed to verify the temperature setting of the incubator and S3 measured the ambient temperature. All units in the system were interconnected with 10 mm polypropylene pipes supported with steel wire. All experiments were performed under laboratory conditions with ambient temperature of 20 ± 0.5°C and relative humidity of approximately 20%.

The drying protocols investigated were as follows: *System A* had 175 g of ash placed within the sieve and 50 mL of anion–exchanged urine was added in each treatment at incubator temperature of 40°C; *System B* had 100 g of ash placed in the sieve with 50 mL of anion–exchanged urine added in each treatment at incubator temperature of 40°C; *System C* had 100 g of ash placed in the sieve with 50 mL of anion–exchanged urine added in each treatment at incubator temperature of 50°C; *System D* had 125 g of biochar placed in the sieve with 50 mL of ion–exchanged urine added in each treatment at temperature of 45°C (See Table 1). For all systems, the air suction flow rate was fixed at 1 $L.min^{-1}$.

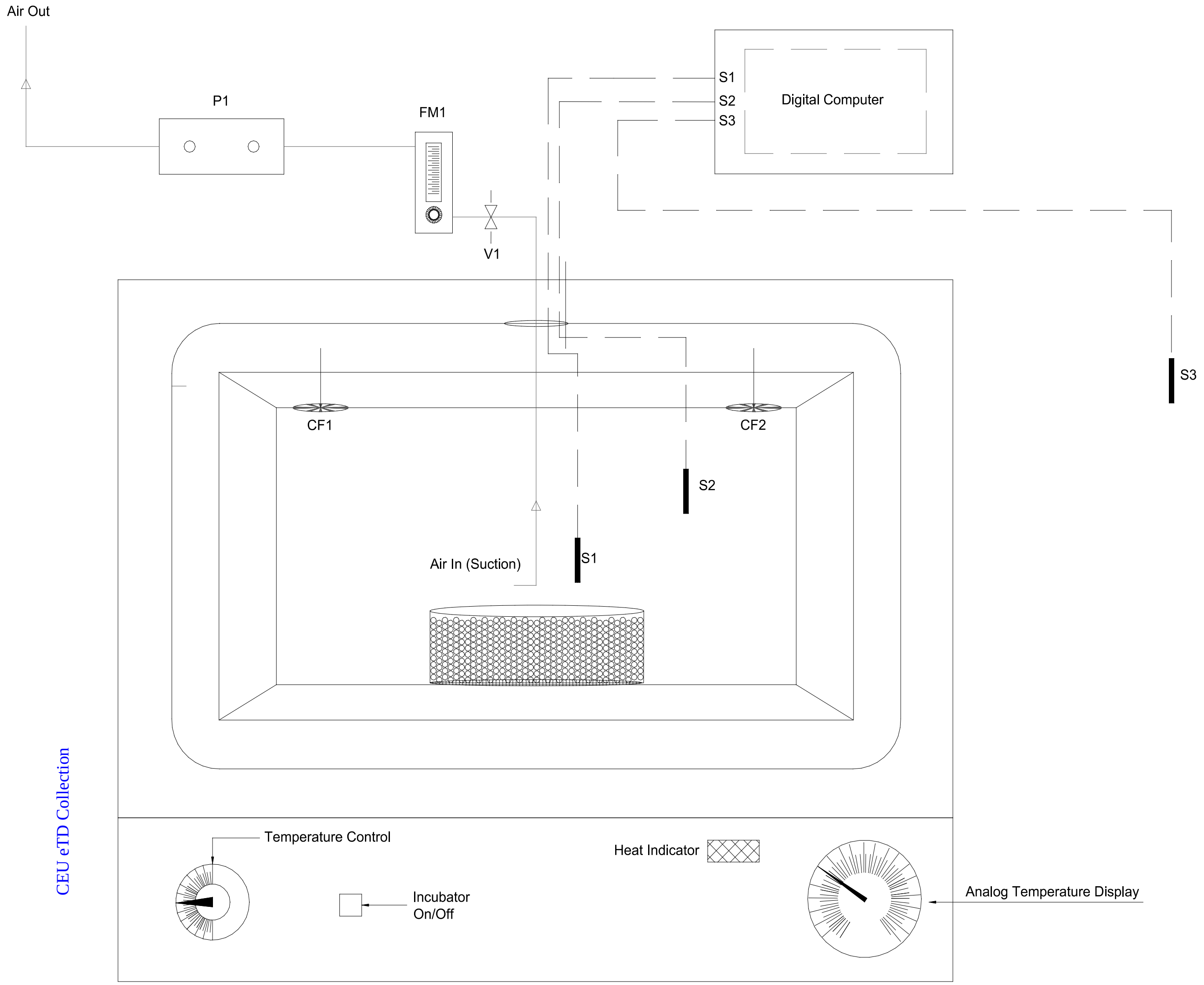
Prior to *Systems A* to *D*, three additional drying protocols were also investigated wherein, 150 g of ash was added to *System E* (round bottom flask), *System F* (cylindrical flask), and *System G* (conical flask) (Appendix AX 8–10). These Systems were not studied after the end of two treatments (50 mL urine per treatment) due to considerably large drying times (48 h).

Table 1: Various drying protocols investigated in the study

System	Drying Media	Urine loading (mL)	Incubator Temperature (°C)
A	175 g Ash	50	40
B	100 g Ash	50	40
C	100 g Ash	50	50
D	125 g Biochar	50	45

In each treatment run, the weight loss corresponding to the removal of moisture from the samples was monitored. In convective drying, the rate exhibits an inverse relationship with time; temperature dependency is high in the initial phase but negligible at or near saturation (Pillai 2013). Consequently, for each treatment, the drying was ceased when it was observed that the system reached the end of the falling rate period (or the beginning of the constant drying rate period). At the end of every seven treatments, the ash was monitored for change in $pH_{1:5}$ and was considered to be saturated (or exhausted) when $pH_{1:5} \leq 10.5$. At this point, the ash was thoroughly mixed and analysed for its elemental composition.

Fig. 4: Schematic diagram for drying of ion–exchanged human urine studied in *Systems* A–D; *Illustration by Author*



2.4. *Physicochemical analysis*

The pH of the urine samples was measured using a radiometer electrode (PHC2011–8, Denmark). The drying media was monitored for change in $pH_{1:5}$ by periodically withdrawing 5 g of the sample from the drying containers and diluting it deionised water at room temperature; after measurement, the ash and water was returned to the drying container. The initial moisture content was determined by oven drying method at 105°C. Bulk density was measured by standard method described elsewhere (Mailler et al. 2016).

Tot–N, Tot–P, NH_4–N were analysed by Spectroquant® test kits (Merck KGaA, Darmstadt, Germany) number 14763 (Tot–N), 12543 (Tot–P), and 14544 (NH4–N) with concentrations ($mg.L^{-1}$) determined colorimetrically using a Nova 60 photometer (Merck KGaA, Darmstadt, Germany). All urine samples were filtered through a 0.45 µm syringe filter (Sarstedt, Germany) prior to analysis.

The ash and biochar were characterised for tot–N and tot–C by Dumas combustion method on an elemental analyser (LECO TruMac® CN, USA). PO_4–P, K, Ca and Mg concentrations were measured by Inductively Coupled Plasma – Optical Emission Spectrometry (ICP Optima 7300 DV, Perkin Elmer®, USA).

2.5. *Mathematical modelling of urine drying*

In order to understand the rate and mechanisms involved in the removal of moisture from the mixture of urine and ash, mathematical modelling was carried out using drying data obtained for *System A* (Fig. 4). Corollary to Newton's law of cooling, the rate of drying should vary in proportion to the difference between the moisture content of the sample initially (MC_o) and at equilibrium (MC_e). The same can be expressed as Moisture Ratio (MR)

wherein, $MR = MC_i - MC_e / MC_o - MC_e$; MC_i represents the moisture content at any time '*i*' and MC_e was assumed to be 1%.

The ash/urine drying curve obtained as a function of time was tested against ten empirical and semi–empirical models by non–linear regression analysis as discussed in Section 3.3. Coefficient of determination (R^2), Residual Sum of Squares (*RSS*), Root Mean Square Error (E_{RMS}) and reduced Chi–Square (χ^2) values (Eq. 2–4) were determined to select the mathematical equation that best described the drying phenomenon (Simha et al. 2016). All statistical analysis was performed using XLSTAT (Microsoft Corporation, USA).

$$RSS = \sum_{i=1}^{n} \left(MR_{exp,i} - MR_{pred,i}\right)^2 \quad (2)$$

$$E_{RMS} = \left[\frac{1}{n}\sum_{i=1}^{n} \left(MR_{exp,i} - MR_{pred,i}\right)^2\right]^{1/2} \quad (3)$$

$$\chi^2 = \frac{\sum_{i=1}^{N} \left(MR_{exp,i} - MR_{pred,i}\right)^2}{n - N} \quad (4)$$

It is acknowledged that most of the moisture removal in the drying of natural products occurs within the falling rate period (Özdemir and Devres 1999). The application of Fick's second law of unsteady–state diffusion (Eq. 5) to the experimental drying data can then allow interpretation of the mechanisms involved in the removal of moisture from the drying sample. It is assumed however that the drying media is one–dimensional, homogeneous and has uniform heat and moisture diffusion (Hashemi et al. 2009).

The Fickian equation can be solved as depicted in Eq. 6 by considering the ash particles to be of spherical geometrical configuration that undergo negligible shrinkage during the drying process. Further simplification can be carried out when the Fourier number ($D_{eff} \times t/r^2$) is larger than 0.1 so as to neglect all the terms in Eq. 6, except the first one to yield Eq. 7 (Akpinar

2006). The effective moisture diffusivity is then calculated by the method of slopes through a plot of ln(*MR*) versus time. The assumption of isothermia is justified given the complexities in the process that involves simultaneous mass and heat transfer within, and from, the drying sample (Di Scala and Crapiste 2008).

$$\frac{dMR}{dt} = D_{eff} \frac{d^2MR}{dx^2} \quad (5)$$

$$\frac{X_t - X_e}{X_0 - X_e} = \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp\left(- n^2 \frac{\pi^2 D_{eff} t}{4L^2} \right) \quad (6)$$

$$MR = \frac{8}{\pi^2} \exp\left(\frac{-\pi^2 D_{eff} t}{4L^2} \right) \quad (7)$$

2.6. Drying optimisation

Since the drying process is likely to be influenced by several factors which can be measured, controlled and adjusted, Response Surface Methodology (RSM) was employed. RSM is a set of mathematical and statistical techniques that help understand, develop, improve and optimise the functional relationship between input variables (standalone as well as interactive influence) and the response of interest (rate of drying in this case) (Baş and Boyacı 2007). Central Composite Rotary Design (CCRD), a conventional RSM model was used due to its applicability in optimising processes where complex interactions among input variables exist. A four factorial–five level CCRD was set up with X_1 – incubator temperature (°C), X_2 – outlet air flow rate (L.min^{-1}), X_3 – ash loading (g) and X_4 – urine loading (mL), chosen as the independent variables; the desired response (*Y*) expressed the drying rate as litres of urine dried per day in one square meter of wood ash (L.day^{-1}.m^{-2}). The functional relationship between the response and the variables was evaluated through Eq. 8 with the objective of maximising the drying rate; X_i represents the independent variables, a_0, a_i, a_{ii}, a_{iii}, a_{ij} and a_{ijk} are model coefficients for the intercept, linear, squared and cubic terms while the last two model constants represent the cross–product terms to depict the interactions between the independent variables.

Design Expert (V.7, Stat–Ease Inc., USA) was used to formulate a set of 30 experiments, regress the experimental data against the third–order polynomial equation (Eq. 8) and select the optimal values. Randomisation of the sequence of the experiments was done to inhibit the effect of uncontrolled variables.

$$\begin{aligned} Y = {} & a_0 + a_1X_1 + a_2X_2 + a_3X_3 + a_4X_4 + a_1a_2X_1X_2 + a_1a_3X_1X_3 + a_1a_4X_1X_4 + a_2a_3X_2X_3 \\ & + a_2a_4X_2X_4 + a_3a_4X_3X_4 + a_{11}X_1^2 + a_{22}X_2^2 + a_{33}X_3^2 + a_{44}X_4^2 + a_{123}X_1X_2X_3 + a_{124}X_1X_2X_4 \\ & + a_{134}X_1X_3X_4 + a_{234}X_2X_3X_4 + a_{11}a_2X_1^2X_2 + a_{11}a_3X_1^2X_3 + a_{11}a_4X_1^2X_4 + a_1a_{22}X_1X_2^2 + a_1a_{33}X_1X_3^2 \\ & + a_1a_{44}X_1X_4^2 + a_{22}a_3X_2^2X_3 + a_{22}a_4X_2^2X_4 + a_2a_{33}X_2X_3^2 + a_2a_{44}X_2X_4^2 + a_{33}a_4X_3^2X_4 + a_3a_{44}X_3X_4^2 \\ & + a_{111}X_1^3 + a_{222}X_2^3 + a_{333}X_3^3 + a_{444}X_4^3 \end{aligned} \tag{8}$$

Statistical significance of the model, the influence of input variables and goodness of fit of the obtained data was checked through Fischer–Test and Analysis of Variance (ANOVA) at 95% confidence interval. Optimum conditions were chosen based on values of the desirability function according to Derringer’s desired function method ($0 \leq di \leq 1$); here, ‘0’ depicts an undesirable response and ‘1’ depicts the optimal response (Roosta et al. 2014). Desirability functions were developed within the range of the input variables investigated subject to the following goals: maximum drying temperature, urine loading and minimum ash loading and air flow rate.

2.7. Psycho–social, demographic and cultural assessment of producer attitudes [†]

The geographical scope of the present study was restricted to the administrative boundaries of Vellore district in the Indian state of Tamil Nadu (Fig. 5). The choice of the study area was purely motivated by its proximity to the principal site of research for the current study (VIT University, India; vit.ac.in) and the familiarity of the area and its

[†] Demographic data sourced from Census if India (2011) and Department of Economics and Statistics (2015)

inhabitants to the author. Vellore district lies between 12°15'–13°15' N and 78°20'–79°50' E and encompasses an area of 6,077 km^2. According to the latest population census, the district is home to 3,936,331 people, 56.7% of whom live in rural areas. Hinduism is the predominant religion (88%) followed by Christianity (6%) and Islam (5%). Vellore is primarily agrarian with a gross sown area of 1,974.5 km^2 that provides employment to 153,211 cultivators and 254,999 main agricultural labourers in addition to 21,897 marginal cultivators and 136,956 marginal agricultural labourers. More than two–thirds of the cultivators are male; 29.5% of the cultivators in the district are female. Further, nearly one–fourth of the population is made up by *Dalits*[‡] or Scheduled Castes (SCs) and Scheduled Tribes (STs).

Information gathering via surveying has seen several technological advances over the years with computer–assisted web interviews commonly used by several institutions (Bryman 2015). However, < 5.5% households in Vellore district own a computer and even among these, < 2.3% have access to internet (Census of India 2011). Hence, in this study it was deemed more fruitful to administer the surveys as face–to–face interviews where surveyors recorded answers of cultivators on a predesigned questionnaire. To do this, ten surveyors with good command over the local language and dialects were trained between November 2015 and January 2016 on the concept of ecological sanitation and human waste recycling. The survey was administered to 120 cultivators who were selected through random sampling of the district farm register. Prior to the interview, all the cultivators were informed about the purpose of the survey and its topical theme and that the survey was voluntary, strictly for academic research and completely anonymous; written consent was provided by all the respondents for using the survey data in the present study. In line with good surveying practices, the respondents were thanked before and after the interviews were conducted.

[‡] See Abbreviations/Glossary for definition (page xiii)

A preliminary survey of the study area was carried out to determine most appropriate times of the day when the cultivators could be approached to ensure high response rates. For instance, in the town of Arakkonam, it was determined that the best time of the day to approach the farmers was just after lunch when most farmers take a short break from farming and therefore, were more inclined to participate in a conversation.

The questionnaire included a series of 22 sequential, closed–ended questions with multiple–choice answers. It consisted of three broad sections: the purpose of *Section I* (questions 1–7) was to establish the socio–economic and cultural profile of the cultivators, *Section II* (questions 8–13) provided details on their farms and the type of farming they were engaged in, while *Section III* (questions 14–22) provided insights into the cultivator's perceptions, attitudes, inclinations and willingness to shift to the use of human excreta based fertilisers (See Table 2).

In addition to recording participant responses, the surveyors were directed to observe the facial expressions and change in attitude of the respondents to specific questions (*Section III* of the questionnaire). Bearing in mind the perceptive nature of the survey, the demographical characteristics of the study area and potential for non–response, in comparison to the rest of the survey the questions in *Section III* were deemed as 'sensitive'. In randomised face–to–face interviews, there is always room for respondents to become uncooperative and sceptical (Kuk 1990) as they are required to answer either 'yes' or 'no' and hence, take a stand. In such cases, facial expressions and body language can help comprehend the reasons for non–response.

Ten pre–test surveys were carried out after which the questionnaire was reordered and refined. Particularly, given the inherent socio–cultural and psychological sensitivities of people towards the notion of using human excreta as fertilisers, it was prudent that these questions were asked towards the end of the survey and were preceded by relatively less sensitive questions in which the respondents were asked to provide their opinions from someone else's point of view.

Fig. 5: Location of the study area (Vellore District, Tamil Nadu) in India

In these questions, the cultivators were asked to place themselves in their neighbour's, relative's, friend's or colleague's shoes to have a more respondent–friendly survey. In the pre–test survey, the difficulty of attaining responses to questions that farmers had little or no information was noted. Hence, although central tendency bias was avoided by providing close–ended ‘yes’ or ‘no’ choices, an option of ‘cannot say’ or ‘no opinion’ was provided in certain questions of *Section III* since no information package or material was given to the cultivators prior to the survey. In any case, additional information was gathered by introducing an alternative response of ‘cannot say’ since it sheds light on the lack of knowledge among the respondents.

Table 2: Survey questions circulated among cultivators in Vellore

Que.	Question Statement	Options
15	Do you feel there is difference between Cow and HU*?	2
16	Do you know anyone who used or uses HU?	2
17	How would you feel if…..	
17.1	Your neighbour started using HU on his/her farm	2
17.2	Someone you know started using HU on his/her farm	2
18	Do you think people in the market place would buy food grown using HU	3
19	Do you think HU can be used as a fertiliser	3
20	Do you think it would be a good idea to use HU to fertiliser your crops?	4
21	Would you buy and use dry fertiliser (urea) safely manufactured from HU?	6
22	Would you consider using human faeces on your land as fertiliser?	4

*HU: Human Urine

To analyse the survey data, all positive responses (yes) were assigned numerical value of 2 and all negative ones (no) were assigned value of 1. The mean ($1 \leq \mu \leq 2$) depicted the probability of the response being positive (yes). The response, ‘cannot say’ was also assigned a numerical value of 1 since it is not indicative of a positive response/attitude and the objective of the survey was to assess the general attitude (positive versus negative) towards the use of human excreta for crop production. The data was processed in order to understand whether the respondent perceptions and attitudes towards human waste recycling differed by their socio–demographic variables. Chi–squared test (χ^2) and one–way analysis of variance

(ANOVA) was used to estimate variations in demographic variables with two and more than three categories, respectively. Level of significance was fixed at 0.05 with p–values < 0.05 considered statistically significant. Evaluating responses of *Section III* against the demographic variables is necessary since the analysis does not end with mere enumeration of the level of acceptance of human waste recycling. In this study it was equally important to gain insights into why the cultivators with positive attitudes had such attitudes in the first place and of course, to understand the factors inhibiting the acceptance of waste recycling among respondents with a negative or non–positive attitude. All statistical analysis was carried out using R, version 3.3.0 RC. Graphical illustrations were made using the ggplot2 (V 2.1.0) and circlize (V 0.3.7) packages.

3. Results and Discussion

3.1. Anion–exchange: alkalinisation and stabilisation

The investigations over the potential of anion–exchange as pre–treatment for alkalinisation of urine was initiated by examining the volumetric resin dosage required to achieve a pH ≥ 11.5. Human urine contains relatively large quantities of Cl^- as NaCl which is readily exchanged with OH^- ions. The anionic strength in urine varies as: $HCO_3^{1-} < Cl^- < NO_3^- < PO_4^{3-} < SO_4^{2-}$ (Putnam 1971). The average theoretical exchange capacity of urine is 0.22 $eq.L^{-1}$ while that of the resin used in the study is 1.25 $eq.L^{-1}$. Hence, in theory, a resin loading of 17.6% (v/v) should be sufficient to exchange all the anions and necessitate the required pH elevation through addition of OH^- ions to the urine.

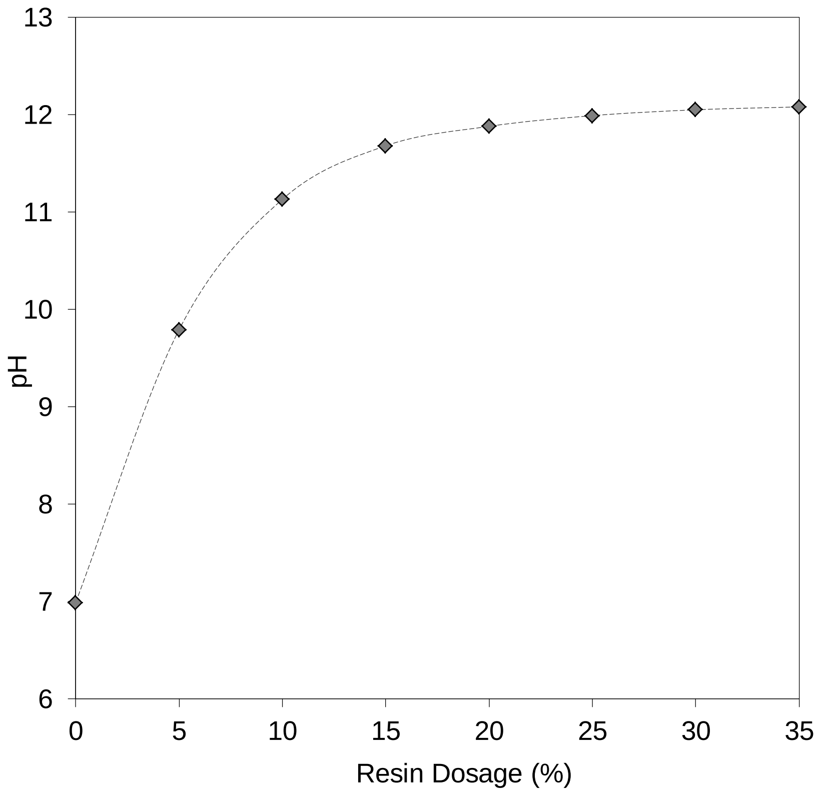
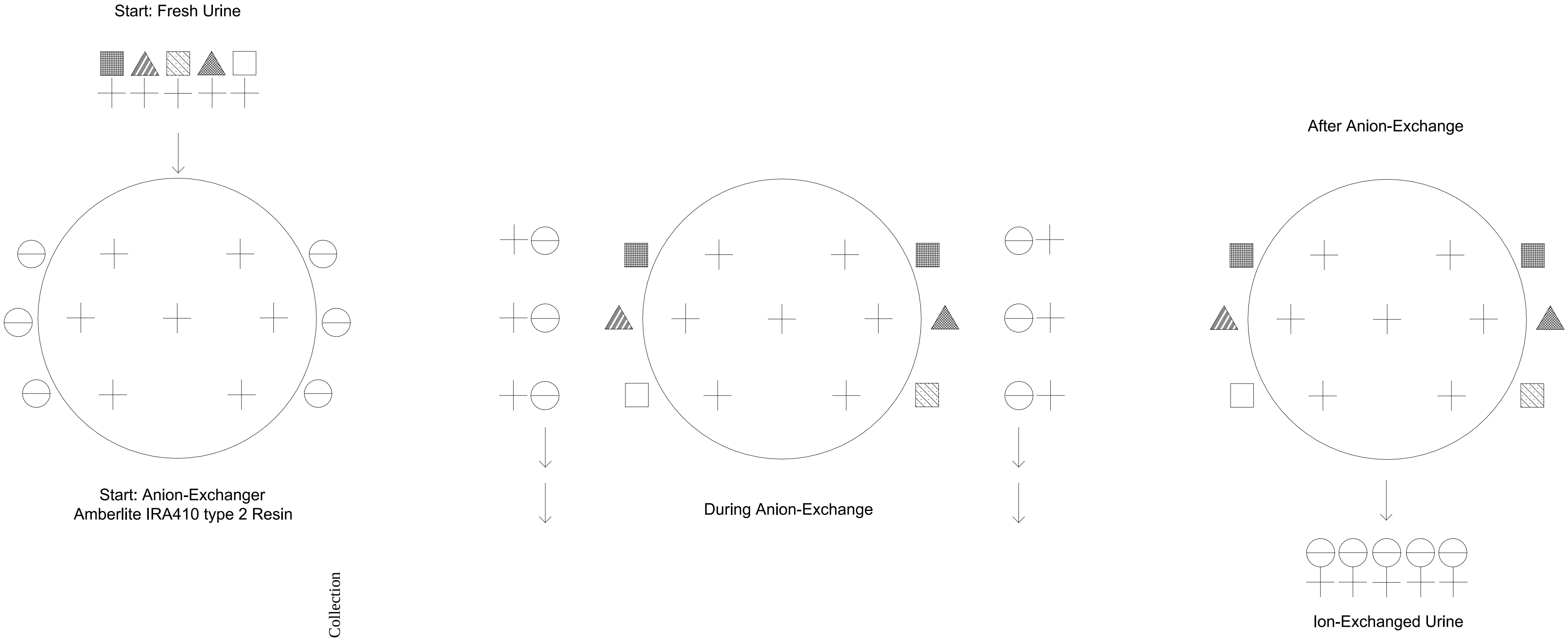


Fig. 6: Effect of resin loading on urine pH

As seen through Fig. 6, 67% and 70% increase in pH was observed at 15% and 20% resin loading, respectively. Further addition of the resin had minimal effect on the pH (<1.7%).

Fig. 7: Schematic representation of anion–exchange of urine by AmberliteTM IRA410 type–2; *Illustration made by the Author*



This is probably because the resin was able to exchange all the anions (Fig. 7). Since the anion concentration of urine can vary considerably (Putnam 1971), a 20% v/v resin loading was considered to be adequate; this provided a safety buffer of 2.4% more than the theoretical capacity.

3.1.1. Effect of storage temperature on hydrolysis and pH of ion–exchanged urine

To gain insights into the thermal stability of the nutrients in the ion–exchanged urine, samples were stored at three different incubator temperatures (20°C, 37°C and 50°C). In fresh urine, more than 80% of the N occurs as urea which is relatively stable while the rest of the N (< 7%) occurs as ammonia–N bound in inorganic compounds as well as in organic compound matrices (Lind et al. 2001). As seen in Fig. 8, on Day 0, due to anion–exchange, 2.78% loss of N was observed. This loss is attributed to ammonia released due to dissociation from inorganic ammonium salts (Eq. 9, Eq. 10).

$$NH_4 + OH^- \leftrightarrow NH_3(aq) + H_2O \tag{9}$$

$$NH_3(aq) \leftrightarrow NH_3(g) \tag{10}$$

However, following this, the total–N content of the samples at 20 and 37°C remained unchanged (median value of 3.5 g.L^{-1} N) whereas it decreased to 3.4 g.L^{-1} N at 50°C. Since all the flasks were covered with aluminium foil, the flasks represented closed headspace systems. The amount and type of headspace determine the partial pressure of NH_3 and therefore the potential for ammonia volatilisation loss (Tilley et al. 2008). In a closed system, volatilisation losses are minimal due to the equilibrium that exists between ammonia and ammonium as seen in Eq. 10 and hence the total–N concentrations remained stable over the investigated time period.

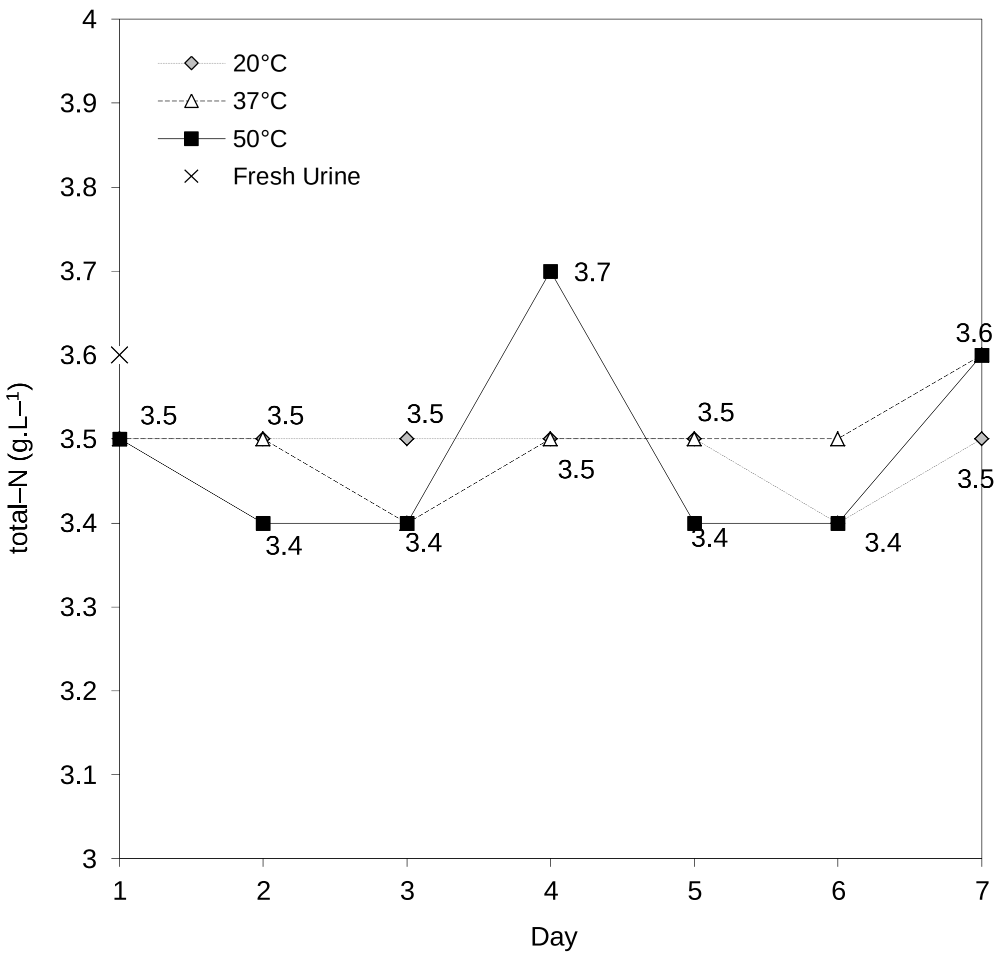


Fig. 8: Variation in total–N content in anion–exchanged urine with temperature

However, to understand the extent of hydrolysis of the ion–exchanged urine with storage at various temperatures, NH_4–N measurements were performed at the end of Day 14 and compared with those in the fresh urine sample at Day 0. As seen in Table 3, the combination of high pH and temperature resulted in very low hydrolysis of urea; this is presumably due to inhibition of the urease–positive bacteria at high temperature and pH. The peak hydrolysis was 3.62% of total–N on Day 14 for urine stored at 50°C which is indicative of the stability of the ion–exchanged urine and its nutrients at all the investigated temperatures. However, during storage, the pH and temperature displayed an inverse relationship with the drop in pH being least at room temperature and highest at 50°C (Fig. 9). The drop in pH can be explained by several factors: (i) urea hydrolysis which results in the formation of CO_2 (weak acid) and NH_3 (weak base) (Zhigang et al. 2008); (ii) thermal degradation of organic compounds in urine including organic ammonium salts which again results in release of CO_2 and formation of carbonic acid (Putnam 1971). It was thus established that anion–exchange and storage of urine at temperatures between 20°C and 37°C in a closed system results in insignificant hydrolysis for a period of two weeks after which pH falls below the threshold value of 10.5.

Table 3: Variation in form and concentration of N in ion–exchanged urine with temperature

Sample	Total–N ($mg.L^{-1}$)[a]	NH_4–N ($mg.L^{-1}$)[b]	% Hydrolysis*
Fresh Urine (Day 0)	3500	36	1.029%
Ion–Exchanged Urine (Day 0)	3500	36	1.029%
Ion–Exchanged Urine (Day 14, 20°C)	3500	31	0.886%
Ion–Exchanged Urine (Day 14, 37°C)	3400	37	1.088%
Ion–Exchanged Urine (Day 14, 50°C)	3400	123	3.618%

* % hydrolysis = a/b

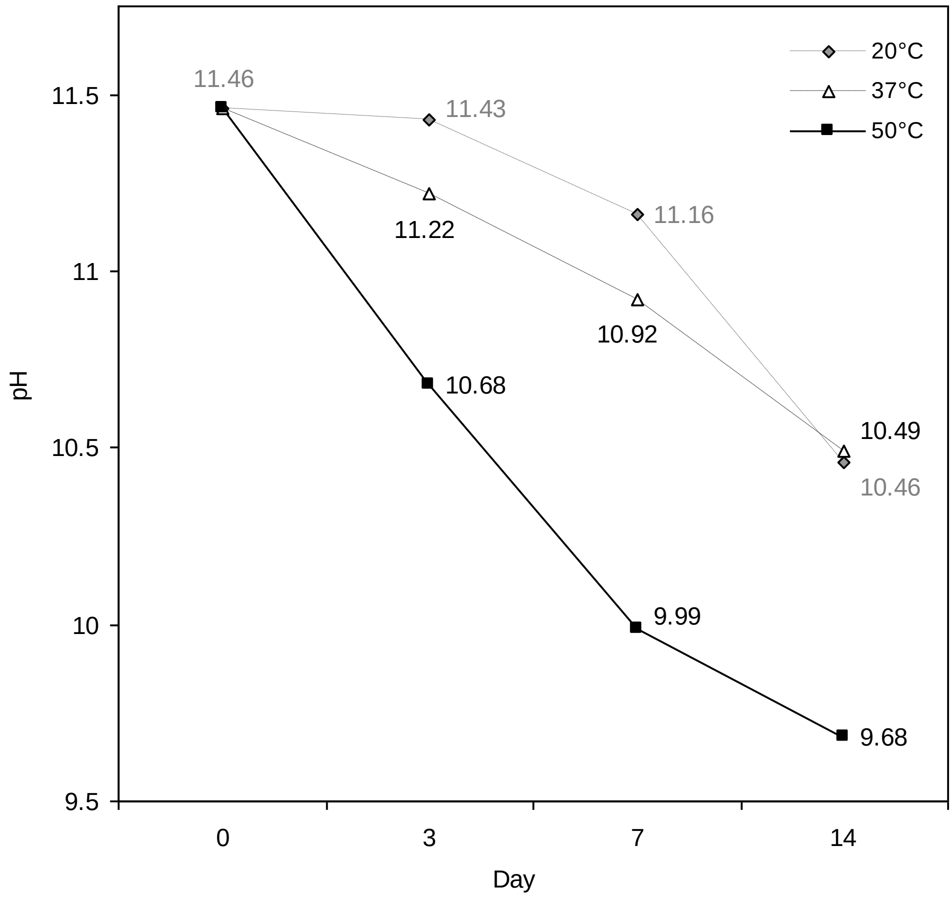


Fig. 9: Change in pH of anion–exchanged urine at various temperatures over time

3.1.2. Effect of urine diversion on alkalinisation

Allowing only certain proportions of fresh urine to interact with the resin through batch experiments provides insights into the design of a potential urine diverting toilet bowl wherein, not necessarily, all the urine has the possibility to interact with the resin. In event of flow channelling of the urine as it passes through the resin, it is essential to ensure adequate stabilisation of the urine occurs through alkalinisation to result in final pH of ≥ 10.5. Hence, the rationale behind diverting a portion of the fresh urine over the anion–exchange resin is twofold: (i) to estimate the minimum amount of urine that needs to pass through the resin and result in a pH of ≥ 10.5 and (ii) to minimise the number of regeneration runs that need to be carried out to replenish the resin for use in subsequent cycles.

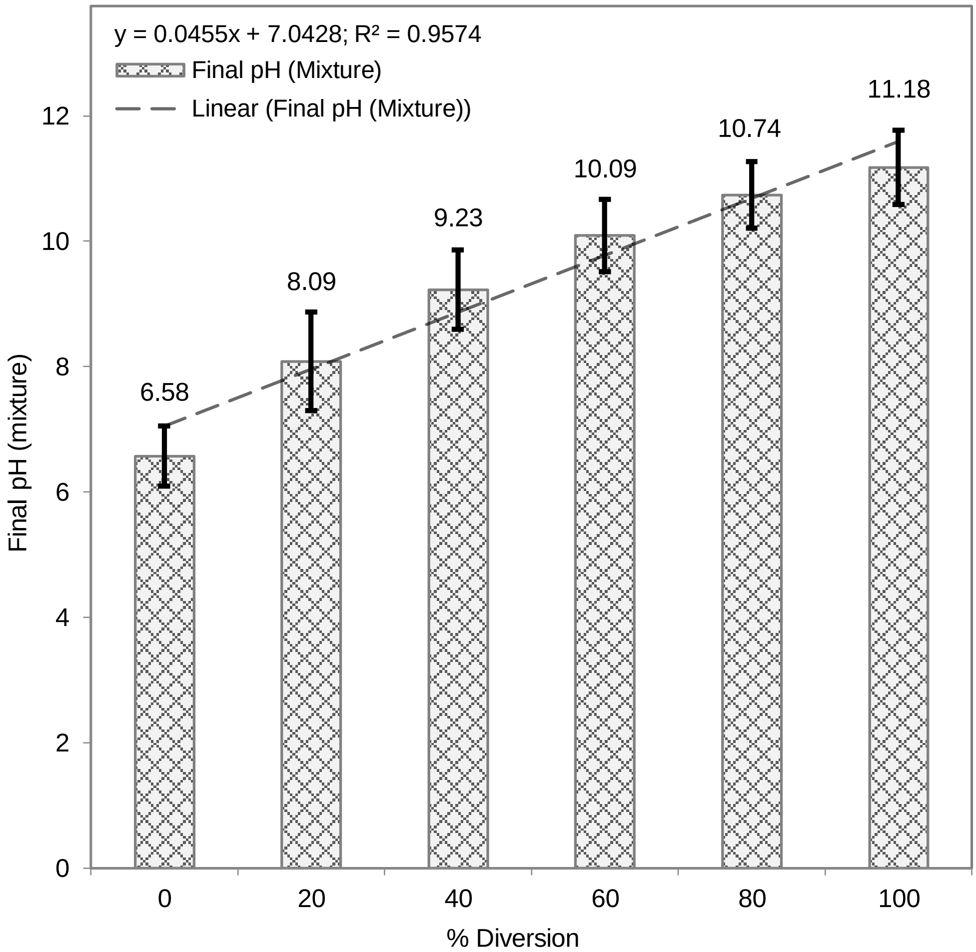


Fig. 10: Effect of resin loading on alkalinisation of urine

To ensure sample representativeness, 50 fresh urine specimens were collected at different times of the day from volunteers with varied dietary preferences. The initial pH of urine varied as 6.61 ± 0.71. The final pH attained by the various urine fractions as a consequence of diverting fixed proportions through the resin is provided in the Appendix AX1. As seen in Fig 10, increasing the volume of fresh urine that passes through the resin increases the final pH of the mixture; as diversion is increased from 20% to 100%, pH increases from 8.09 ± 0.8 to 11.18 ± 0.6, respectively. This follows the corollary that higher the volume of urine that interacts with the resin, greater is the ion–exchange due to higher availability of anions in the solution which in turns increases the concentration of OH^- in the urine resulting in higher pH. This was validated by the high positive correlation (R^2 = 0.95, P < 0.001) observed for the effect of diversion on the urine pH (Fig. 10). On the basis of these 50 experimental runs it can be concluded that at least 75% volume of the urine in a diverting toilet must pass through the resin to attain the threshold pH of ≥ 10.5 in the storage tank. This establishes the lower limit for volumetric flow and will be an important criterion in designing a urine diverting bowl that incorporates the anion–exchange resin for alkalinisation.

3.2. Urine drying as studied through various protocols

3.2.1. Characterisation of the drying media

The initial pH of wood ash was 12.88 in *System A* and *System B* while it was 13.01 in *System C*. The average pH of the prepared biochar was 12.61. The initial properties of the wood ash used in the present study are as follows: moisture content – <1%, bulk density – 0.46 $g.cm^{-3}$, particle density – 2.22 $g.cm^{-3}$ and total porosity – 79.3%. Similarly, the biochar was also characterised for its initial properties: moisture content – 6.3%, bulk density of 0.29 $g.cm^{-3}$, particle density of 0.74 $g.cm^{-3}$ and total porosity of 63% (Berger 2012). The initial elemental (nutrient) compositions of the drying media are discussed in detail in Section 3.2.6.

The pH of the ion–exchanged urine used in all the drying runs was 10.21 ± 0.5 with density of 0.988 ± 0.02 g.cm^{-3}.

3.2.2. *Rationale for sieve–based urine drying*

A sieve–based drying setup that combined the salient advantages of batch bin drying and batch tray drying was utilised in all four systems investigated for urine drying (*Systems* A–D). The rationale behind using a perforated mesh as a mechanical support for the final layer of the drying media (ash or biochar) is (i) to minimise any heat transfer resistance that can potentially be offered by the drying containers (glass, plastics, stainless steel in this case); and (ii) to provide a relatively better pathway for heat distribution from the heating mantle to the drying media and also within the media itself (See Fig. 11).

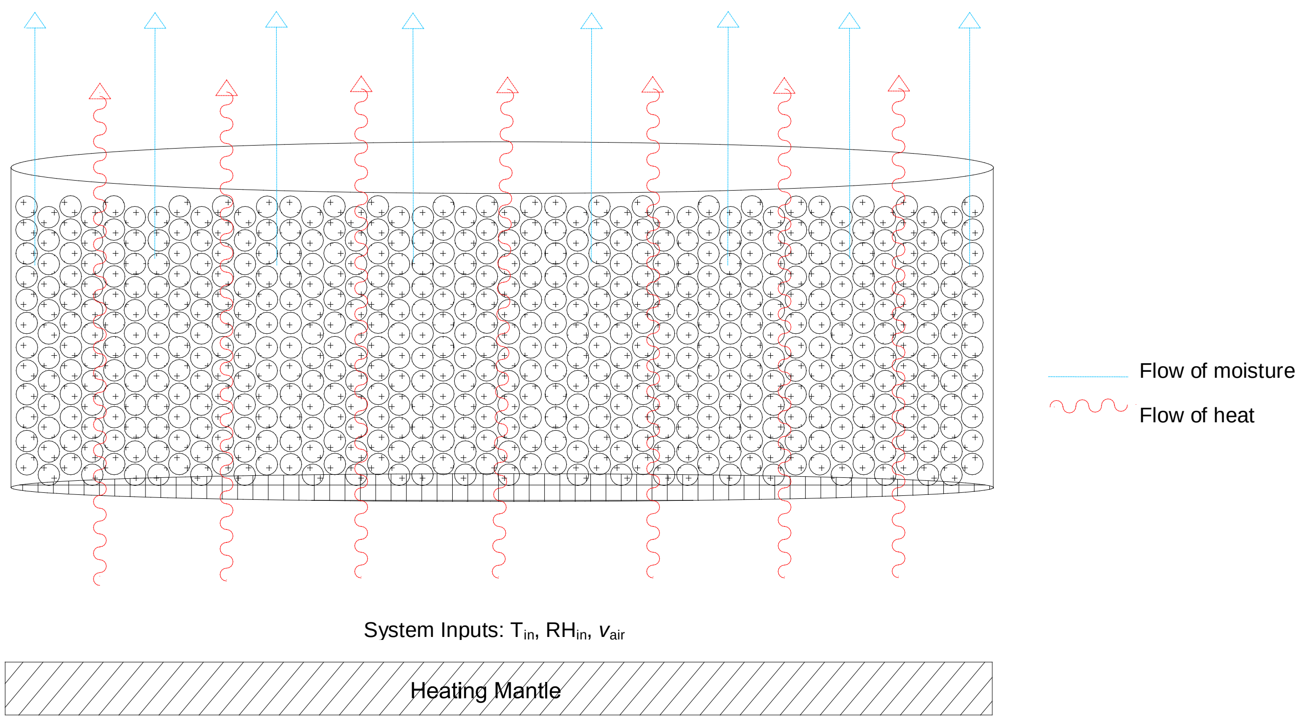


Fig. 11: Heat and mass transfer during urine drying over sieve trays; *illustration by Author*

Surely, a negative temperature gradient exists within the bed and that, the bed temperature decreases with height as has been observed elsewhere (Wang and Chen 1999). Contrarily, there also exists a positive moisture gradient (top to bottom) in the bed which is created due to suction pressure just above the top layer of the drying media. Both these gradients govern the moisture diffusion and evaporation from the drying media. However, any moisture gradient in the bed is eliminated when the drying media is thoroughly mixed and due to the cooling period that occurs after the last drying run (Thompson et al. 1968).

3.2.3. Comparative analysis of urine drying rates

The principal objective in drying was to minimise the volume of the anion–exchanged urine through (alkaline) dehydration while simultaneously establishing the maximum nutrient recovery potentials of the drying media in the various protocols investigated. Results of the urine drying experiments for different protocols (*System A* to *D*) have been summarised in Tables 4–7. In *System A*, where 50 mL ion–exchanged urine was added in each drying run to 175 g (fixed) of wood ash, an average drying rate of 6.57 ± 0.4 $L.day^{-1}.m^{-2}$ was observed. Initially, for runs 1 to 7, the drying time was fixed at 360 min based on initial experiments; however, from run 8 onward, the drying time was gradually reduced to 310 ± 11.5 min. For the same amount of moisture removal, lesser drying time should translate into higher urine drying rates and the same was observed from run 8 onward (6.64 ± 0.4 $L.day^{-1}.m^{-2}$). The reduction in time is achieved by virtue of the reduction in the height of the ash bed which undergoes compaction with every new addition of urine until it attains its equilibrium height. Presumably, bed compaction causes reduction in bed voidage which is inversely proportional to the heat and mass transfer coefficients (Dwivedi and Upadhyay 1977).

In *System B*, wherein, the ash loading was reduced to 100 g, a slightly better average drying rate (6.70 ± 0.52 $L.day^{-1}.m^{-2}$) as well as lesser drying time (310 ± 15 min) was observed in comparison to *System A*. Moreover, operating the drying at 50°C nearly doubled the drying rate for *System C* which recorded the highest rate (11.93 ± 1 $L.day^{-1}.m^{-2}$) across all the protocols studied. *System C* also required the least drying time (192 min) to process the same volume of urine; this is expected since increasing the drying temperature from 40 to 50°C, nearly doubles the moisture holding capacity of air (humidity ratio).

For the biochar based urine drying (*System D*), initial runs with 50 mL of ion–exchanged urine per treatment (125 g biochar loading; fixed) resulted in relatively lower drying rates (5.16 ± 1.1 $L.day^{-1}.m^{-2}$) as against those obtained for *Systems A* and *B*. Subsequently, taking advantage of the inherent ability of biochar to hold water, the urine loading was increased to 100 mL per treatment which resulted in increasing the drying rate to 6.40 ± 0.6 $L.day^{-1}.m^{-2}$.

3.2.4. Cumulative drying capacities in the investigated protocols

By simultaneously considering the total amount of urine processed per unit mass of the drying media as well as the cumulative time required for drying that amount of urine, it is possible to evaluate and cross–compare the drying capacity of each system at exhaustion. In all protocols, the drying was stopped when the $pH_{1:5}$ of the drying media reached ≤ 10.5. At this point, the total amount of urine processed by *Systems* A–D was 1.8, 1.6, 1.55 and 1.42 L, in that order. As seen in Fig. 12, 1 kg of ash in *System A* can dry 9.15 L of urine at 40°C within 8 days. In comparison, *System B* with lower ash loading at the same drying temperature can process ~14.5 L of urine per kg of wood ash within one week. *System D* with biochar as the media exhibits capacity (13.5 L of urine.kg of ash^{-1}) similar to that of *System B*. *System C* exhibits both, the best drying capacity as well as the shortest drying time; here, 1 kg of ash heated at 50°C completely dries 15.2 L of urine in just 4.15 days.

In order to provide a broader perspective to these results, let us consider a household with 4 members each producing 1.2 L of urine per day (Mihelcic et al. 2011); for every household, on average, this translates into 4.8 $L.day^{-1}$ and 144 $L.month^{-1}$. To completely process 144 L of urine, the amounts of wood ash required would be: 15.7 kg (*System A*), 9.98 kg (*System B*) and 9.47 kg (*System C*) while the amount of biochar required would be 10.67 kg. If the drying system operates every day to process 4.8 L of urine per household, the time required to operate the system would be the average drying time observed across the different protocols as mentioned earlier. Alternatively, the urine could be collected cumulatively, stored and stabilised through anion–exchange for a fixed time period (as a first guess, two weeks based on results in Fig. 9), and the dried continuously. The latter could also facilitate the interlinking of various individual toilets with anion–exchange resins in their bowls and channel urine from various households to a semi–centralised drying system.

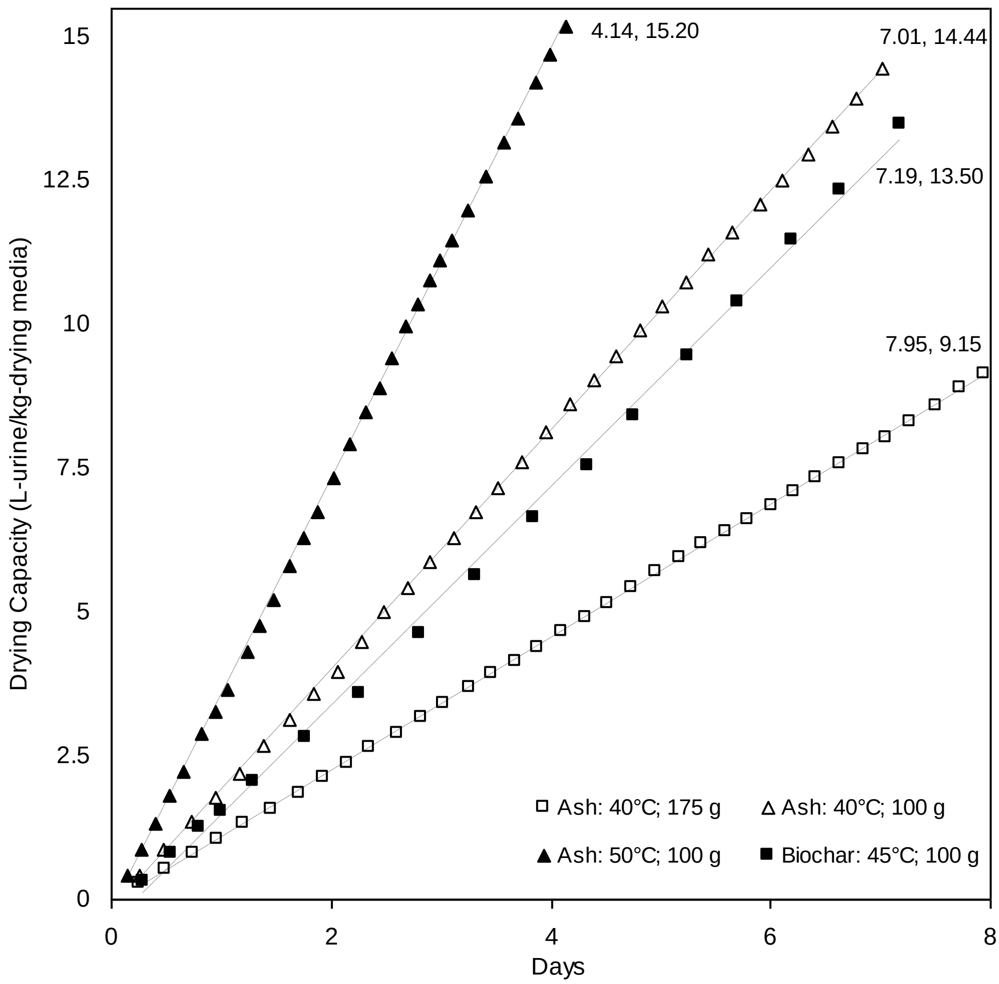


Fig. 12: Drying capacity for different drying media and protocols (lines represent linear fit to the experimental data, $P < 0.001$; data labels represent x: drying time, y: total urine processed in that order)

Table 4: Experimental results for urine drying in *System* A					
Run	**Ash_{in} (g)**	**$Urine_{in}$ (mL)**	**Drying Time (min)**	**Urine ρ ($kg.m^{-3}$)**	**Drying Rate ($L.day^{-1}.m^{-2}$)**
A_R1	175	50	360	1.023	5.80
A_R2	175	50	360	1.012	6.00
A_R3	175	50	360	0.987	6.02
A_R4	175	50	300	1.015	6.75
A_R5	175	50	360	0.986	6.48
A_R6	175	50	360	0.990	6.56
A_R7	175	50	360	0.995	6.25
A_R8	175	50	310	0.995	6.80
A_R9	175	50	315	0.975	6.79
A_R10	175	50	310	1.069	6.60
A_R11	175	50	345	0.998	6.35
A_R12	175	50	325	1.022	6.53
A_R13	175	50	300	1.011	7.25
A_R14	175	50	320	0.989	6.77
A_R15	175	50	300	0.978	6.82
A_R16	175	50	310	1.016	5.56
A_R17	175	50	305	1.100	6.58
A_R18	175	50	310	1.014	6.79
A_R19	175	50	310	1.004	6.60
A_R20	175	50	300	0.980	7.21
A_R21	175	50	300	0.996	6.93
A_R22	175	50	310	0.996	7.35
A_R23	175	50	310	0.978	6.33
A_R24	175	50	310	0.996	6.43
A_R25	175	50	300	0.996	5.66
A_R26	175	50	300	1.005	6.31
A_R27	175	50	300	0.967	6.79
A_R28	175	50	300	0.971	6.43
A_R29	175	50	300	0.971	6.44
A_R30	175	50	305	0.953	6.42
A_R31	175	50	300	0.973	6.24
A_R32	175	50	300	0.961	6.11
A_R33	175	50	320	0.961	6.99
A_R34	175	50	330	0.977	7.20
A_R35	175	50	320	0.968	7.43
A_R36	175	50	325	0.968	6.82
Summary	**175**	**1800**	**11450**	**0.994**	**6.57**

Table 5: Experimental results for urine drying in *System B*					
Run	**Ash_{in} (g)**	**$Urine_{in}$ (mL)**	**Drying Time (min)**	**Urine ρ ($kg.m^{-3}$)**	**Drying Rate ($L.day^{-1}.m^{-2}$)**
B_R1	100	50	360	1.008	5.62
B_R2	100	50	330	1.017	6.33
B_R3	100	50	360	0.990	6.16
B_R4	100	50	310	1.122	6.30
B_R5	100	50	315	0.997	6.44
B_R6	100	50	310	0.976	6.96
B_R7	100	50	345	0.999	6.19
B_R8	100	50	325	1.016	6.53
B_R9	100	50	300	1.014	6.25
B_R10	100	50	320	0.971	7.18
B_R11	100	50	300	0.976	8.14
B_R12	100	50	310	0.976	6.27
B_R13	100	50	290	0.997	7.28
B_R14	100	50	300	0.997	6.80
B_R15	100	50	300	0.976	7.22
B_R16	100	50	300	0.976	6.43
B_R17	100	50	300	0.976	6.73
B_R18	100	50	330	0.976	7.34
B_R19	100	50	310	0.974	7.28
B_R20	100	50	310	1.003	6.75
B_R21	100	50	300	0.994	6.25
B_R22	100	50	300	0.994	6.90
B_R23	100	50	300	1.005	6.50
B_R24	100	50	300	0.971	6.83
B_R25	100	50	300	0.971	7.18
B_R26	100	50	305	0.964	5.87
B_R27	100	50	360	0.964	6.41
B_R28	100	50	310	0.969	6.66
B_R29	100	50	320	0.969	6.37
B_R30	100	50	330	0.969	6.86
B_R31	100	50	320	0.995	7.16
B_R32	100	50	325	0.995	7.28
Summary	**100**	**1600**	**10095**	**0.991**	**6.70**

Table 6: Experimental results for urine drying in *System C*					
Run	**Ash$_{in}$ (g)**	**Urine$_{in}$ (mL)**	**Drying Time (min)**	**Urine ρ (kg.m^{-3})**	**Drying Rate (L.day^{-1}.m^{-2})**
C_R1	100	50	210	0.963	9.66
C_R2	100	50	185	0.981	11.06
C_R3	100	50	185	0.991	11.36
C_R4	100	50	185	0.979	12.09
C_R5	100	50	170	0.979	12.04
C_R6	100	50	240	0.990	12.36
C_R7	100	50	180	1.005	10.61
C_R8	100	50	180	0.991	10.05
C_R9	100	50	240	1.000	12.55
C_R10	100	50	170	0.957	12.38
C_R11	100	50	170	0.966	12.62
C_R12	100	50	220	0.965	12.32
C_R13	100	50	180	0.961	12.40
C_R14	100	50	180	0.961	12.51
C_R15	100	50	210	0.981	13.06
C_R16	100	50	210	0.979	12.65
C_R17	100	50	210	0.974	12.72
C_R18	100	50	180	0.971	10.75
C_R19	100	50	180	0.986	13.59
C_R20	100	50	180	0.986	14.06
C_R21	100	50	150	0.992	12.47
C_R22	100	50	150	0.992	12.45
C_R23	100	50	150	0.996	10.90
C_R24	100	50	150	0.996	10.92
C_R25	100	50	210	0.993	12.16
C_R26	100	50	240	0.987	11.28
C_R27	100	50	240	0.987	11.32
C_R28	100	50	180	0.961	10.68
C_R29	100	50	240	0.967	12.42
C_R30	100	50	180	0.967	12.34
C_R31	100	50	200	1.013	11.96
Summary	**100**	**1550**	**5955**	**0.981**	**11.93**

Table 7: Experimental results for urine drying in *System D*					
Run	Biochar$_{in}$ (g)	Urine$_{in}$ (mL)	Drying Time (min)	Urine ρ (kg.m^{-3})	Drying Rate (L.day^{-1}.m^{-2})
D_R1	125	50	420	0.960	3.52
D_R2	125	50	360	0.960	6.17
D_R3	125	50	375	0.990	5.66
D_R4	125	50	295	0.997	4.68
D_R5	125	50	410	0.993	5.78
D_R6	125	70	675	0.971	5.38
D_R7	125	100	720	1.011	4.92
D_R8	125	100	780	0.988	6.34
D_R9	125	100	750	0.988	6.17
D_R10	125	100	750	0.988	6.41
D_R11	125	100	720	0.991	5.74
D_R12	125	100	600	0.990	6.70
D_R13	125	100	690	0.974	7.06
D_R14	125	100	660	1.000	6.83
D_R15	125	100	720	0.996	7.00
D_R16	125	100	615	0.998	6.45
D_R17	125	100	810	0.961	6.75
Summary	**125**	**1420**	**10350**	**0.985**	**6.13**

3.2.5. Alkalinity of the drying media – pH as the threshold and limiting factor

This section seeks to provide possible explanations for the drop in pH of the drying media that was observed over time and due to which the drying had to be stopped at the threshold pH (≤ 10.5). As mentioned earlier, the drying media was considered exhausted (or saturated) when its $pH_{1:5}$ reached a value of ≤ 10.5. Earlier research in wastewater treatment indicates that alkalinisation is an effective process for pathogen inactivation and hence, the drying was stopped at this threshold value (Winker et al. 2009). Alkalinisation in combination with moisture removal at high temperatures should be sufficient for complete inactivation and disinfection of human urine although further feasibility studies are necessary to validate this. Fig. 13 illustrates the drop in $pH_{1:5}$ of the drying media as the drying progresses over time. The drop in pH was linear (R^2 > 0.87) in all the three systems. A primary reason for the pH drop is the presence of carbon dioxide in the air which passes through the media. At the beginning of every experimental run, the drying media holds its highest concentration of water (97% of the urine) which then decreases over time as the drying progresses. The hypothesis for pH drop is that, as air passes over the moisture–laden drying media, CO_2 gets absorbed and dissolved resulting in an increase in hydrogen ion (H^+) concentration (and hence, reduces alkalinity) as follows;

$$CO_2 + H_2O \leftrightarrow H_2CO_3 \leftrightarrow HCO^{3-} + H^+ \leftrightarrow CO_3^{\ 2-} + 2H^+ \qquad (11)$$

The relative concentrations of CO_2 (aq), carbonic acid (H_2CO_3), bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}) during the absorption of CO_2 (g) by aqueous solutions is a function of the solution temperature and pH (Wolf–Gladrow et al. 2007). In high pH environments such as the one in the drying media ($pH_{1:5}$ at t = 0 is > 12.5), CO_3^{2-} is the dominant species. Although the concentration of CO_2 in the inlet air was not measured in this study, it is safe to assume that CO_2 (aq) in the media increases with time as more carbon dioxide gets stripped from the incoming air. While it is acknowledged that the moisture content in the media decreases over time, it is also understood that every new addition of urine replenishes it. As CO_2 (aq) increases and pH decreases due to carbonic acid formation, the equilibrium (Eq. 11) shifts towards the left and the concentrations of (HCO_3^-) and H^+ increase. Simultaneously, any buffering reaction that removes H^+ from the equilibrium only drives the process further ultimately resulting in more H^+ production (Mitchell et al. 2009). Relating this with the phenomenon of ocean acidification, decrease in pH would increase the buffer factor (or Revelle factor) thereby reducing the buffering effect of the drying media (if any) and cause further uptake of CO_2 (g).

Human urine contains Ca (30–90 $mg.L^{-1}$) and Mg (20–205 $mg.L^{-1}$) as inorganic chlorides, sulphates and phosphates (Putnam 1971). Chemical analysis of the pre–treated ash also suggests that Ca (241 ± 9 $g.kg^{-1}$) and Mg (23 ± 0.6 $g.kg^{-1}$) are present in appreciable quantities. While these elements are present as ions in urine, those in the drying media possibly get ionised when they come in contact with water. Presumably, the concentration of these ions also determines the shifting of the CO_3^{2-} equilibrium which results in further CO_2 uptake and H^+ production. Lastly, another process driving down the pH could be the thermal degradation of urea, ammonium salts (11% of the total solutes) and organic compounds in human urine. Any formation of ammonia would push down the pH since it is a weak base as discussed earlier in Section 3.1.1 (See Fig. 9).

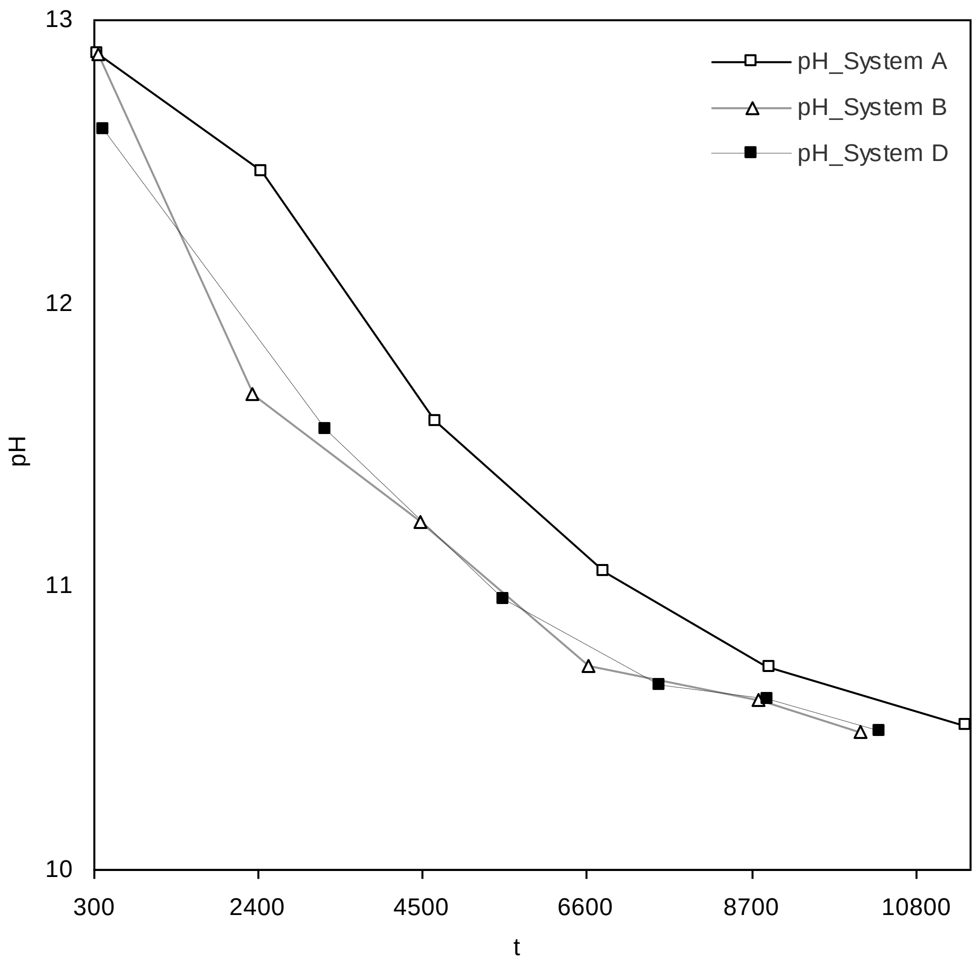


Fig. 13: Change in $pH_{1:5}$ of the drying media with drying time

Hence, the primary factors causing the pH drop in the media could be carbonic acid formation due to CO_2 absorption, intrinsic (urine) and extrinsic (media) buffering action of Ca and Mg compounds and ammonia (weak base) formation from thermal degradation of urea and organic nitrogenous compounds in urine.

3.2.6. *Mass and nutrient balance for urine drying*

To establish the potential for volume minimisation through dehydration and nutrient recovery via inhibition of urea hydrolysis (alkalinisation), a mass balance was carried out for *Systems* A–D. In all drying protocols, a volume reduction of ≥ 97% was achieved. Urine drying can thus effectively minimise the volumes of human excreta that require 'treatment' each year. The mass of drying media required to process the annual amount of urine excreted by an average individual (500 $kg.yr^{-1}$) was estimated to be 54, 34, 33 and 11 kg in *Systems* A–D, respectively. In effect, this suggests that the use of a household urine drying unit would make each person accountable for just 21–64 kg of nutrient rich products (urine + drying media) instead of 500 kg of waste (urine) every year. This quantity fades significantly in comparison to the average per capita municipal solid waste generated each year (483 $kg.yr^{-1}$) (Hoornweg and Bhada–Tata 2012).

As seen in Fig. 14 and Fig. 15, subjecting fresh urine to anion–exchange resulted in a slight loss of N (~ 6%) which is attributed to the volatilisation of free ammonia–N at high pH. Based on the tot–N concentrations in the ion–exchanged urine, 76.5, 49.6, 73.8 and 71.8% N was retained in *Systems* A–D, respectively. Here, I consider *System B* as an outlier and attribute the anomalous results to human error. Prior to experimental run # 29, it was observed that the addition of fresh urine led to seepage through the sieve thereby causing leaching of the adsorbed nutrients from the sieve bottom. This illustrates the significance of a good mechanism for urine distribution over the media for sieve–based urine drying to be effective. Alternatively, it is also possible that the media, over the course of drying and especially near saturation (pH ≤ 10.5) undergoes a high degree of compaction and could have resulted in channelling the urine to the sieve bottom. A potential solution to this would be periodic mechanical mixing of the media. I therefore disregard any results obtained for *System B* from hereon.

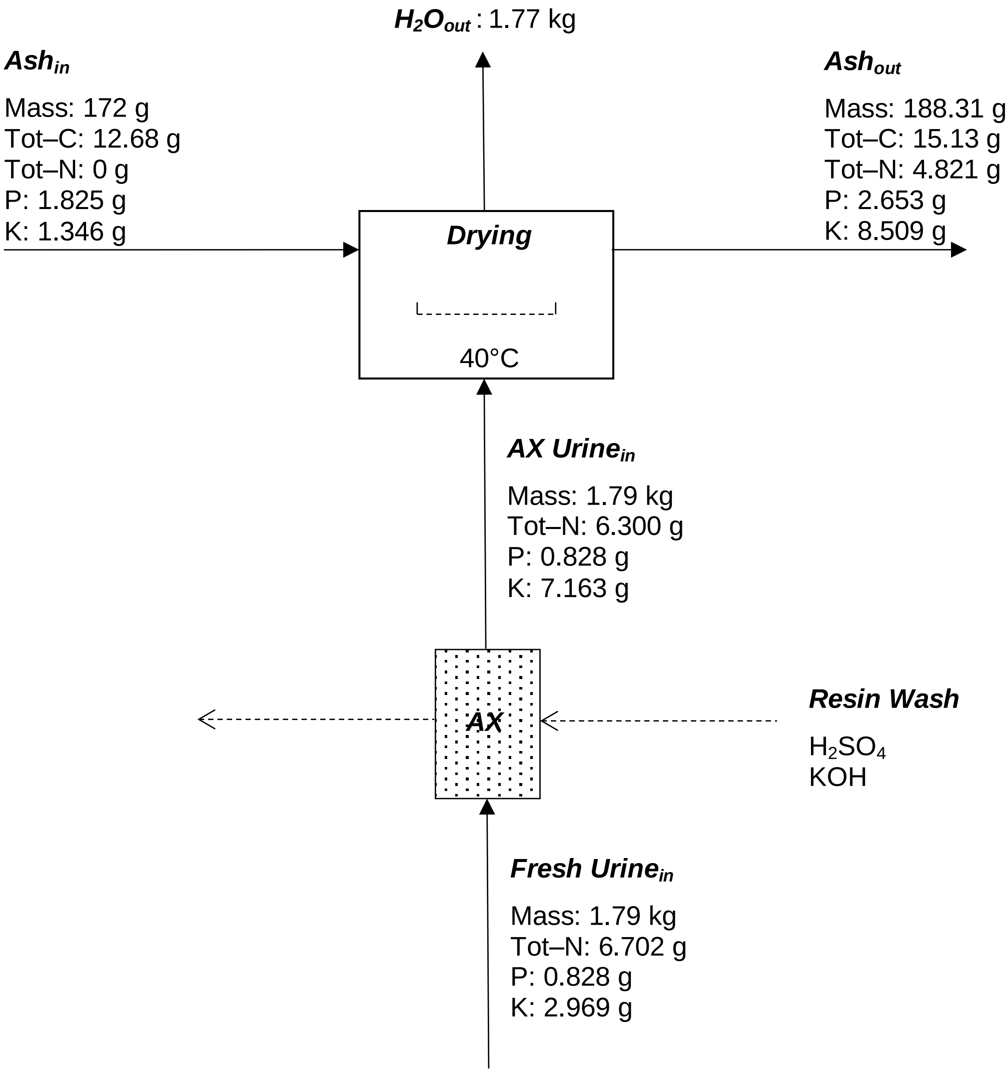


Fig. 14: Mass and nutrient balance for *System A*

As indicated in Fig. 14 and Fig. 15, all the P and K in the urine was preserved within the media due their non–volatility at the investigated drying temperatures. The particular forms (phosphate, struvite, etc.) in which the P and K compounds are retained was not investigated or quantified in this study. During the ion–exchange of several fresh urine samples, struvite formation was observed as a result of the combination of intrinsic Mg and high pH (> 9). Further struvite formation could have also occurred in the wood ash (Mg: 23 ± 0.6 g.kg^{-1}). With certainty, I can only conclude that the dehydrated media retains all the P and K of which some will be in the form of struvite.

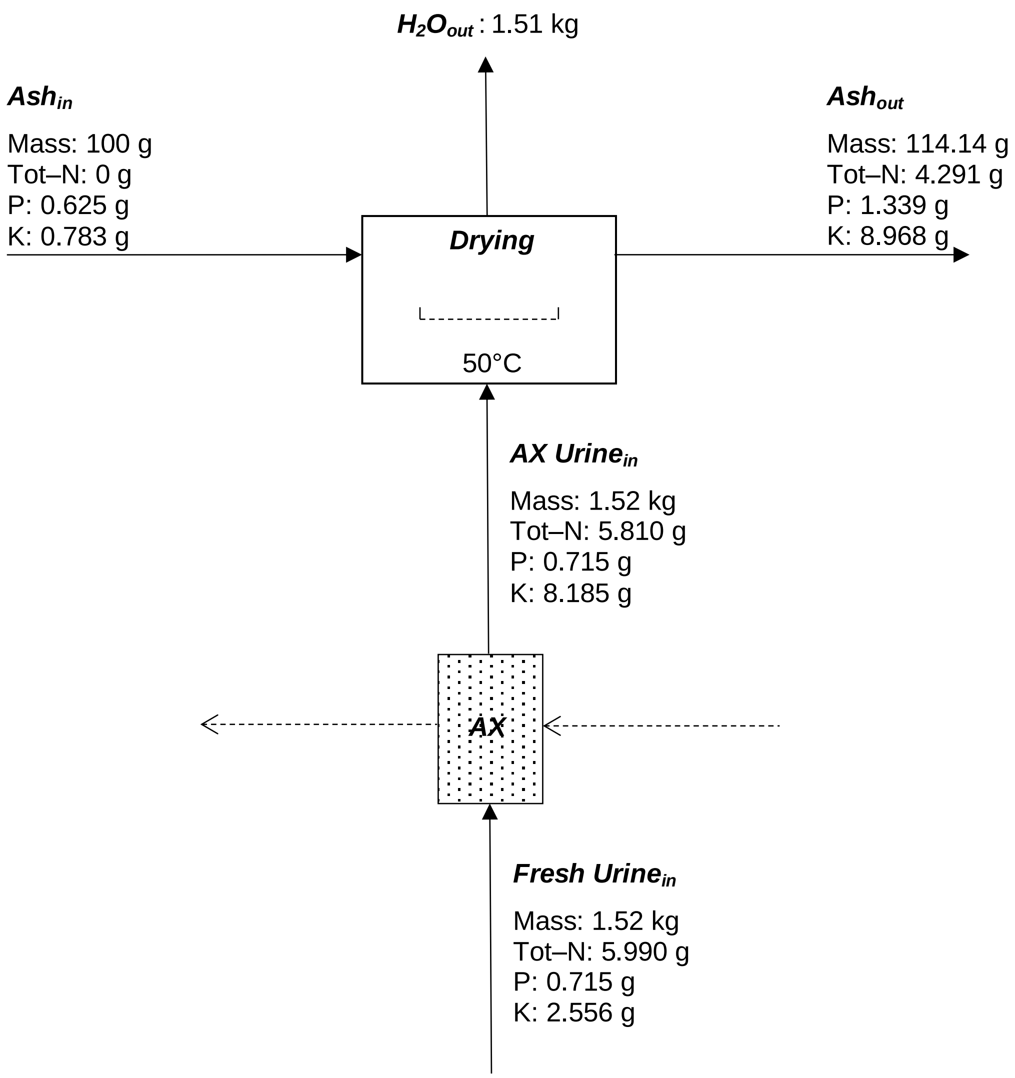


Fig. 15: Mass and nutrient balance for *System C*

Warner (1942) points out that the half–life of urea at 66°C and pH ≥ 12 reduces to less than 5 days. Further, Randall et al. (2016) in their study of $Ca(OH)_2$ assisted urine stabilisation conclude that 40°C could be considered a conservative upper temperature limit to inhibit chemical degradation of urea. In the present study, the maximum N preservation (76.5%) was attained in *System A* which was operated at a temperature of 40°C. It was also observed that increasing the drying temperature to 50°C resulted in considerably higher drying rate (12 $L.day^{-1}.m^{-2}$) but little reduction (< 5%) in N–retention in comparison to the same system operated at 40°C. I attribute this additional loss of N in *System C* to thermal degradation of urea.

Across all the drying protocols, the loss of N varied as 23.5–28%. Based on the conclusions of Randall et al. (2016), Werner (1942) and Chin and Kroontje (1963), this loss can be explained by considering the following statements and Fig. 16;

Region I: The high initial pH of the media (>12.8) could have caused some chemical urea hydrolysis.

Region II: A temperature of 40°C has been put forward only as a tentative upper limit. It is possible that some urea underwent thermal degradation.

Region III: Some loss of urea–N could have occurred due to enzymatic hydrolysis although this loss would have been rather low as the drying was stopped at pH ≤ 10.5. In their experiments with fresh human urine, Randall et al. (2016) find ammonia–N concentration to double only after 27 days indicative of a very low concentration of urease.

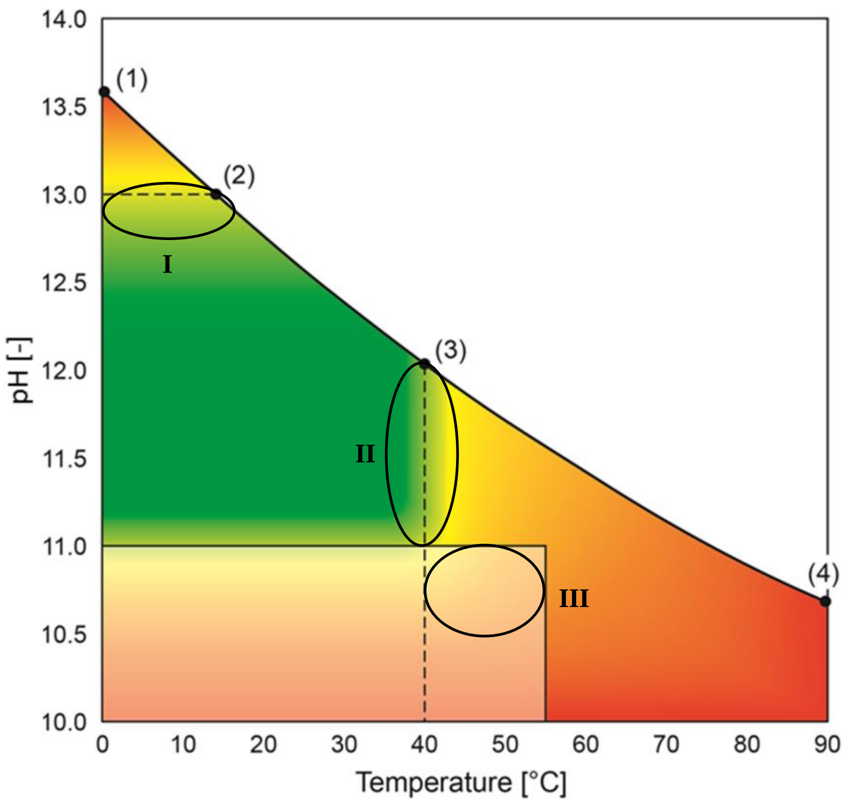


Fig. 16: Design chart indicating regions where negligible urea loss (green), enzymatic urea hydrolysis (bottom rectangular region, pH 10 to 11 and 0–55 °C) and chemical urea decomposition occurs (yellow–orange–red); Adopted and *modified* from Randall et al. (2016)

Following the above discussion it is evident that certain parameters and operating conditions influence the drying and nutrient retention more significantly than the others. In the present study, an appreciable proportion of the N (> 75%) and all of the P and K was recovered in the drying media. However, any further studies on drying that seek to improve the N–retention must take the following tentative suggestions into consideration;

a. Chemical urea hydrolysis at the onset can be inhibited by pre–treating the drying media (in the case of naturally alkaline drying media like wood ash) or by adjusting the dosage of alkalinisation agent (KOH, NaOH) when producing an activated media (like the biochar) in order to have $pH_{1:5} \leq 13$ at day 0.
b. If maximising the N recovery is the process objective, then I recommend the upper limit for drying temperature to be between 35 and 40°C; further research is necessary for identification of this temperature boundary.
c. Alternatively, if maximising the drying rate takes precedence over N retention, a favourable operating regime would be between 40 and 55°C in conjunction with urine to ash ratio of 0.6–0.8.
d. Urine drying is a challenge in process optimisation. Based on the end goal of the process, we can discretely optimise the process conditions to result in maximisation of either % N retention or the drying rate. In Section 3.4, I illustrate how this can be done for the drying rate when using wood ash.

In conclusion, I would also like to stress that the drying media in itself must not be perceived as a limiting factor in the urine drying process. Instead, it is the pH of the media that determines the range within which the drying can be carried out. Any suitable media with natural alkalinity (such as wood ash) can be utilised. Alternatively, as demonstrated in this study through the use of biochar, a drying media can also be produced by base activation of a precursor. It would only add further positive externality to the system if the precursor can also be sourced from substances that are classified as ‘wastes’ such as saw dust. When considering the choice of the media the following attributes must also be taken into consideration: thermal conductivity, mechanical strength, particle size, porosity, moisture holding capacity and initial elemental composition. It is acknowledged that ‘suitability’ of the media is a subjective feature since it is contingent upon its availability and has to be tailored to suit the geographical location, context, user and local circumstances.

3.3. Evaluating the drying of urine against empirical models

In the subsequent section, a mathematical basis for urine drying will be established to understand the mechanisms that control the rate of moisture removal from the drying media. Fig. 17 illustrates the variation of the moisture ratio (*MR*) with drying time for wood ash (175 g) mixed with human urine (50 mL) as investigated in the protocol for *System A*. Over the course of all 36 experimental runs, the total time required for drying was observed to be 318 ± 21.6 min. More than 90% of the drying was completed in less than 300 min; whereas, the time required for MR to reach 0.5 was 135 min which accounted for 39% of the total drying time. Hence, it took 61% of the total drying time for the removal of the residual half of the moisture from the ash.

Under the conditions investigated, the drying curves exhibited smooth curvature indicative of diffusion–controlled mass transfer of moisture from the ash surface (Prabhanjan et al. 1995). It is reiterated here that although a constant rate drying period exists for *System A*, the drying was ceased before it was attained. On ignoring the constant rate period, the drying rate was found to be directly proportional to the moisture content with time.

The effective moisture diffusivity, calculated through the method of slopes for linear ln(*MR*) versus time plots ($R^2 = 0.94$, $P < 0.05$) was found to be 2.03×10^{-11} $m^2.sec^{-1}$. No literature was available on ash or urine drying to compare the obtained effective diffusivity value;

however, it was found to be similar to hot–air drying of other natural products (Maskan et al. 2002; Park et al. 2002; Wang et al. 2007).

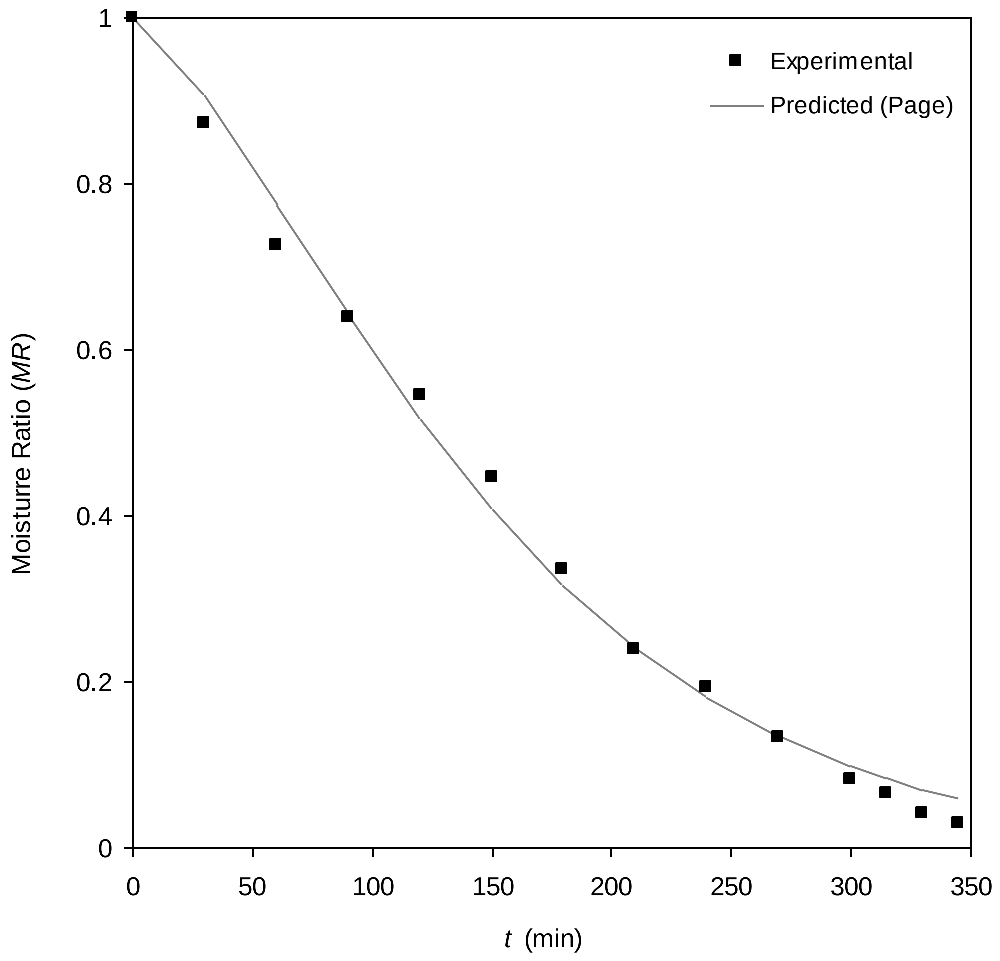


Fig. 17: Drying curve for ash based urine drying (*System A*)

The statistical analysis for regression of the experimental data against 10 empirical and semi–empirical drying models is presented in Table 8. The coefficient of determination was greater than 0.97 for all the equations with *RSS*, E_{RMS} and χ^2 values lower than 1.62, 0.34 and 0.16 respectively.

Table 8: Empirical models, constants and statistical parameters for urine drying				
Empirical Model	**Model equation**	**Model constants**	**Statistics**	
Newton	$MR = \exp(-kt)$	k = 0,0064	RSS	0,0455
			E_{RMS}	0,0570
			χ^2	0,0045
			R^2	0,9906
Page	$MR = \exp(-kt^n)$	***k* = 0,0009**	$\boldsymbol{RSS}$	**0,0088**
		***n* = 1,3703**	$\boldsymbol{E_{RMS}}$	**0,0251**
			$\boldsymbol{\chi^2}$	**0,0009**
			$\boldsymbol{R^2}$	**0,9970**
Henderson	$MR = a \cdot \exp(-kt)$	k = 0,0643	RSS	0,0455
		a = 1,0000	E_{RMS}	0,0570
			χ^2	0,0045
			R^2	0,9906
Logarithmic	$MR = a \cdot \exp(-kt) + c$	k = 0,0064	RSS	0,9429
		a = 1,0000	E_{RMS}	0,2595
		c = 0,2500	χ^2	0,0943
			R^2	0,9906
Wang and Singh	$MR = 1 + at + bt^2$	a = –0,0032	RSS	0,1013
		b = $1{,}0 \times 10^{-05}$	E_{RMS}	0,0851
			χ^2	0,0101
			R^2	0,9903
Diffusion	$MR = a \cdot \exp(-kt) + (1-a) \cdot \exp(-kbt)$	k = 0,1287	RSS	0.0457
		a = 0.0010	E_{RMS}	0.0571
		b = 0,0499	χ^2	0.0046
			R^2	0,9906
Verma	$MR = a \cdot \exp(-kt) + (1-a) \cdot \exp(-gt)$	k = 0,0074	RSS	0,0270
		a = 1,1527	E_{RMS}	0,0439
		g = 1,2500	χ^2	0,0027
			R^2	0,9913
Two term exponential	$MR = a \cdot \exp(-kt) + (1-a) \cdot \exp(-kat)$	k = 0,0093	RSS	0,0123
		a = 1,8762	E_{RMS}	0,0297
			χ^2	0,0012
			R^2	0,9960
Midilli	$MR = a \cdot \exp(-kt^n) + bt$	k = 0,0013	RSS	16,253
		a = 0,2511	E_{RMS}	0,3407
		n = 0,5197	χ^2	0,1625
		b = 0,0000	R^2	0,9882
Two term	$MR = a \cdot \exp(-k_1 t) + b \cdot \exp(-k_2 t)$	k_1 = 2,000	RSS	0,1539
		k_2 = 0,0046	E_{RMS}	0,1049
		a = 0,2103	χ^2	0,0154
		b = 0,7896	R^2	0,9719

Note: MR: Moisture Ratio = $MC_i - MC_e / MC_o - MC_e$;
RSS – Residual Sum of Squares; E_{RMS} – Root Mean Square Error; χ^2 – Chi–Square

$$MR = \frac{MC_t - MC_e}{MC_0 - MC_e} = \exp\left(-0.0009\ t^{1.3703}\right) \quad (12)$$

Both Page and Diffusion models were found to be suitable with corresponding R^2 values of 0.997 and 0.996; however, based on E_{RMS} and χ^2 values, the Page model (Eq. 12) was found to best describe the removal of moisture from the mixture of urine and ash in the examined system (Wang et al. 2007). Similar findings have been reported in literature for convective drying with falling rate behaviour (Mwithiga and Olwal 2005; Giri et al. 2007).

Mathematical modelling of the urine drying process indicated that it can be adequately described by the Page model (Eq. 12) when it is restricted to the falling rate period and under the following experimental conditions: ash loading of 175 g, urine loading of 50 mL, incubator temperature of 40°C and air suction rate of 1 $L.min^{-1}$. This is the first mathematical solution and is helpful in understanding the urine drying kinetics. By incorporating and testing the multiple combinations of logarithmic, linear, Arrhenius, exponential and power expressions in the derived Page model (Pillai 2013), it would also be possible to develop a characteristic drying equation that would be helpful during process scale–up and when designing a household urine drying unit.

3.4. Optimisation of urine drying

As mentioned earlier, urine drying is a challenge in process optimisation. Hence, with the objective of maximising the rate of urine drying, optimisation was performed to identify the most significant factors that influence the drying and to estimate their optimal values.

3.4.1. Statistical analysis

To begin with, the validity of the response surface model was verified and the results of the statistical analysis are presented in Table 9. The model was able to take into account more than 92% of the variability in the experimental data for each response. This meant that the experimental variables investigated accounted for 92% of the total variation in drying rate. Since *P*–value for the model is less than 5% it is safe to assume that at least one factor is statistically significant in determining the output response.

Furthermore, from the test for lack of fit, the *P*–values were found to be low (< 1%) and the hypothesis that the model is adequate in describing the drying process was accepted. The high coefficient of determination (R^2 = 0.92) and low coefficient of variation (CV = 6.57) confirm that the difference between the predicted and experimental drying rates is minimal.

Lastly, adequate precision or signal to noise ratio, which quantifies the range of predicted values at the design points to the average prediction error was calculated to be 8.79; a threshold value of ≥4 is considered desirable for model to be significant and to display adequate model discrimination (Mason et al. 2003).

Table 9: Analysis of Variance (ANOVA) for the response surface cubic fitted model

Source	Sum of Squares	*df*	Mean Square
Residual	1.05163	7	0.15023
Lack of Fit	1.05163	2	0.52581
Pure Error	0.00000	5	0
Cor Total	13.5416	29	
Std. Dev.	0.38759		
Mean	5.89150		
C.V. %	6.57895		
PRESS	151.435		
–2 Log Likelihood	–15.3893		
R–Squared	0.92234		
Adj *R*–Squared	0.67826		
Adeq Precision	8.79250		
BIC	62.8382		
AICc	214.610		

Table 10: Analysis of Variance (ANOVA) for Response Surface Cubic model (aliased)						
Source	**Sum of Squares**	***df***	**Mean Square**	***F* Value**	***P*–value Prob > *F***	**Remarks**
Model	12.49	22	0.568	3.779	**0.0387**	*significant*
X_1–Drying Temperature	3.006	1	3.006	20.01	**0.0029**	*significant*
X_2–Air Flow Rate	0.739	1	0.739	4.921	**0.0620**	*significant*
X_3–Ash Loading	4.452	1	4.452	29.63	**0.0010**	*significant*
X_4–Urine Loading	0.525	1	0.525	3.497	0.1037	
X_1X_2	0.069	1	0.069	0.457	0.5208	
X_1X_3	0.018	1	0.018	0.120	0.7388	
X_1X_4	0.010	1	0.010	0.064	0.8077	
X_2X_3	0.027	1	0.027	0.177	0.6867	
X_2X_4	0.013	1	0.013	0.084	0.7800	
X_3X_4	0.000	1	0.000	0.003	0.9583	
X_1^2	0.754	1	0.754	5.016	**0.0601**	*significant*
X_2^2	0.092	1	0.092	0.614	0.4589	
X_3^2	0.871	1	0.871	5.801	**0.0469**	*significant*
X_4^2	0.005	1	0.005	0.035	0.8566	
$X_1X_2X_3$	0.001	1	0.001	0.003	0.9553	
$X_1X_2X_4$	0.036	1	0.036	0.238	0.6407	
$X_1X_3X_4$	0.006	1	0.006	0.042	0.8433	
$X_2X_3X_4$	0.005	1	0.005	0.033	0.8618	
$X_1^2X_2$	0.060	1	0.060	0.398	0.5482	
$X_1^2X_3$	2.554	1	2.554	17.00	**0.0044**	*significant*
$X_1^2X_4$	0.108	1	0.108	0.717	0.4251	
$X_1X_2^2$	0.625	1	0.625	4.158	**0.0808**	*significant*
$X_1X_3^2$	0	0	–	–	–	
$X_1X_4^2$	0	0	–	–	–	
$X_2^2X_3$	0	0	–	–	–	
$X_2^2X_4$	0	0	–	–	–	
$X_2X_3^2$	0	0	–	–	–	
$X_2X_4^2$	0	0	–	–	–	
$X_3^2X_4$	0	0	–	–	–	
$X_3X_4^2$	0	0	–	–	–	
X_1^3	0	0	–	–	–	
X_2^3	0	0	–	–	–	
X_3^3	0	0	–	–	–	
X_4^3	0	0	–	–	–	

Table 11: Process Optimisation with RSM: Central Composite Rotary Design (CCRD)										
Run	Real variables				Coded variables				Response (Y; $L.day^{-1}.m^{-2}$)	
	X_1	X_2	X_3	X_4	X_1	X_2	X_3	X_4	Experimental	Predicted
1	42	1.25	175	70	1	1	1	1	6.117	4.313
2	42	1.25	125	50	1	1	–1	–1	6.081	6.072
3	38	0.75	175	70	–1	–1	1	1	5.955	5.811
4	40	1	150	60	0	0	0	0	6.202	5.669
5	40	1	100	60	0	0	–1.682	0	6.685	5.818
6	40	1	150	60	0	0	0	0	6.202	6.202
7	38	1.25	175	50	–1	1	1	–1	5.193	5.973
8	40	1	150	60	0	0	0	0	6.202	6.765
9	38	1.25	125	50	–1	1	–1	–1	5.234	5.425
10	42	0.75	175	50	1	–1	1	–1	6.162	6.202
11	38	0.75	175	50	–1	–1	1	–1	5.821	5.745
12	42	1.25	175	50	1	1	1	–1	5.978	5.082
13	40	0.5	150	60	0	–1.682	0	0	6.282	6.202
14	42	0.75	175	70	1	–1	1	1	6.323	6.481
15	44	1	150	60	1.682	0	0	0	6.469	5.826
16	38	0.75	125	70	–1	–1	–1	1	6.081	5.362
17	40	1	150	80	0	0	0	1.682	6.474	5.562
18	42	1.25	125	70	1	1	–1	1	6.224	5.929
19	40	1	200	60	0	0	1.682	0	3.701	6.171
20	38	0.75	125	50	–1	–1	–1	–1	5.962	6.202
21	36	1	150	60	–1.682	0	0	0	4.017	6.77
22	40	1	150	40	0	0	0	–1.682	5.449	5.049
23	38	1.25	125	70	–1	1	–1	1	5.569	6.202
24	40	1	150	60	0	0	0	0	6.202	3.997
25	42	0.75	125	70	1	–1	–1	1	6.625	5.937
26	42	0.75	125	50	1	–1	–1	–1	6.351	6.199
27	40	1	150	60	0	0	0	0	6.202	6.981
28	40	1.5	150	60	0	1.682	0	0	5.066	6.018
29	38	1.25	175	70	–1	1	1	1	5.714	6.578
30	40	1	150	60	0	0	0	0	6.202	6.202

3.4.2. Development of the response surface cubic model

The controlled input variables were correlated to the drying rate (response) through Central Composite Rotary Design (α = ±1.682). The cubic model which takes into account 3–factor interaction was selected as suggested by the software. Non–linear regression of Eq. 8 was performed by default to obtain the regression coefficients, its significance as well as the individual standard error through *F*–test. The Prob > *F*–values for all the coefficients are listed in Table 10. Model terms with Prob > *F* less than 0.05 were considered highly significant and with Prob > *F* less than 0.1 were considered moderately significant. In the cubic model developed for optimising urine drying rate, X_1, X_2, X_4, X_3^2, $X_1^2X_3$ were found to be highly significant; moderate significance was displayed by X_3, X_1^2 and $X_1X_2^2$.

The slight discrepancy between the R^2 and R^2_{Adj} was due to the inclusion of non–significant factors in the model equation (Eq. 13). Ignoring the contribution of the non–significant factors as per the results in Table 10 and reducing the cubic model yields a new equation in terms of the coded factors (Eq. 14).

$$\begin{aligned} Y = {} & 6.202 + 0.613X_1 - 0.304X_2 - 0.746X_3 + 0.256X_4 + 0.065X_1X_2 - 0.034X_1X_3 \\ & - 0.024X_1X_4 + 0.041X_2X_3 + 0.028X_2X_4 + 0.005X_3X_4 - 0.166X_1^2 - 0.058X_2^2 \\ & - 0.178X_3^2 + 0.014X_4^2 - 0.005X_1X_2X_3 - 0.047X_1X_2X_4 - 0.019X_1X_3X_4 \\ & + 0.018X_2X_3X_4 + 0.106X_1^2X_2 + 0.692X_1^2X_3 - 0.142X_1^2X_4 - 0.342X_1X_2^2 \end{aligned} \quad (13)$$

$$Y = 6.202 + 0.613\,X_1 - 0.304\,X_2 - 0.746\,X_3 - 0.166\,X_1^2 - 0.342\,X_1\,X_2^2 \quad (14)$$

Table 11 enlists the experimental and predicted drying rate which was found to vary from 3.7 to 6.7 $L.day^{-1}.m^{-2}$. Good agreement was seen between the theoretical predictions and the observed values (Fig. 18) indicating that the developed model equation adequately captured the drying rate as a function of the input variables. Subsequently, visualisation of the output response was carried out by generating 3–D surface plots and contour plots as a function of two of the independent input variables while keeping the others at a fixed constant value.

Alternatively, a perturbation plot was also drawn to simultaneously visualise the individual contribution of each input variable by keeping all other factors at their central value (Fig. 19).

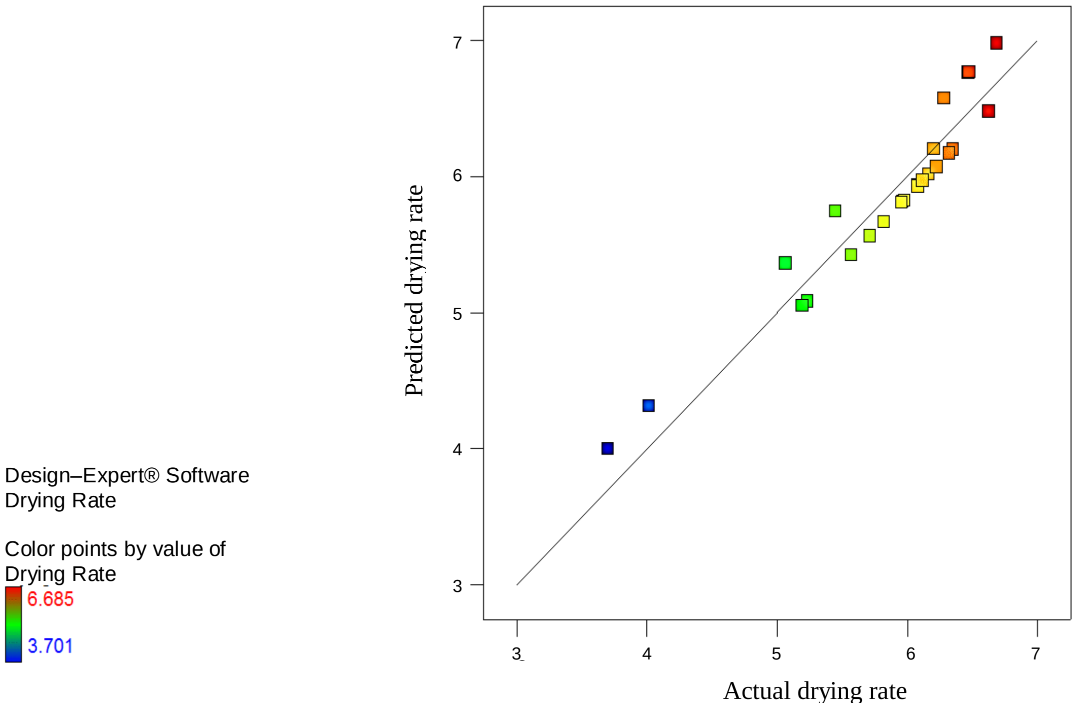


Fig. 18: Experimental and predicted urine drying rates for response surface cubic model

As seen below in the perturbation plot, the output reponse (drying rate) was highly sensitive to incubator temperature and the amount of ash loading wheras, urine loading and air flow rate exhibited relatively moderate influence. In any drying process, the rate of drying exhibits a positive relationship with drying temperature; this was also observed in the ash based drying of urine wherein, increasing the temperature from 36 to 42°C increased the drying rate from 4.01 to 6.47 L.day^{-1}.m^{-2}, respectively (Fig. 20 (a)). An increase in temperature results in decreased drying times due to quicker removal of moisture from the drying surface which in turn enahances the drying rate (Menzies and O'Callaghan 1971). Increasing the temperature increased the driving force for heat and subsequently, mass transfer from the ash to the ambient air in the drying chamber (Parlak 2015). The ease with which moisture was removed from the mixture of urine and ash in the drying chamber at higher temperatures can be attributed to the characterisitc features of falling rate drying (drying was ceased at the end of falling rate period); in the falling rate curve, moisture diffusion from the drying sample is directly proportional to the moisture content of the ash in excess of its equilibrium moisture content (Kaymak-Ertekin 2002).

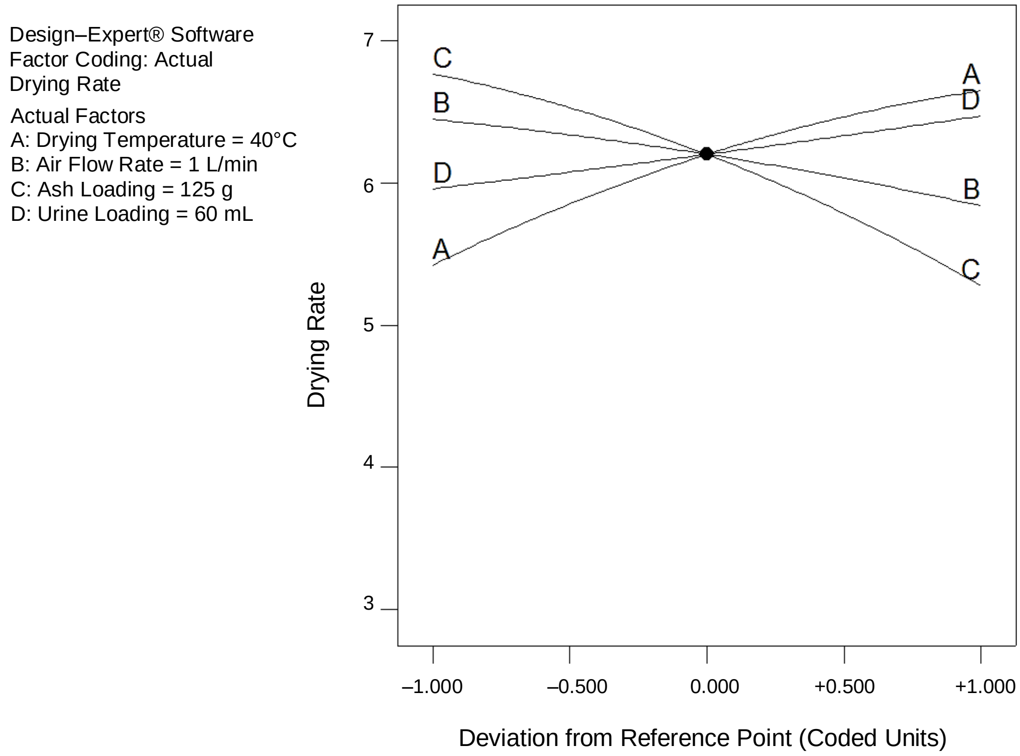


Fig. 19: Perturbation plot for effect of various controlled input variables in RSM

Air flow rate through the drying chamber does not appreciably affect the drying rate at a constant temperature and constant relative humidity (Fig. 20 (e)). However, drying time increases from 335 to 440 min as air velocity increases from 0.5 to 1.5 $L.min^{-1}$. Also, for the system investigated, increasing the air velocity increases the drying rate initially (up to 0.75 $L.min^{-1}$); this is possibly due to reduction in time required to attain the equilibrium drying temperature within the drying chamber (Toğrul and Pehlivan 2003). At air velocity greater than 0.75 $L.min^{-1}$, the rate exhibits an inverse relationship due to larger times required to attain equilibrium as well as due to sub–optimal drying of the ash. Drying rate was maximum (6.63 $L.day^{-1}.m^{-2}$) when air velocity was 0.75 $L.min^{-1}$ and constant operating conditions (temperature = 42°C, ash loading = 125 g, urine loading = 70 mL). Minimum drying rate (5.1

L.day^{-1}.m^{-2}) was observed at the highest air velocity (1.5 L.min^{-1}) in run number 28 (Table 11). Similar observations have been made by others who studied the effect of process variables including that of air flow velocity in the drying of natural materials (Yaldýz and Ertekýn 2001; Kaymak-Ertekin 2002; Toğrul and Pehlivan 2003).

Ash loading had a significant negative correlation (R^2 = 0.86, P < 0.005) with the drying rate. For instance, increasing the ash loading from 125 to 175 g caused a corresponding reduction in rate from 6.3 to 6.1 L.day^{-1}.m^{-2} at 42°C and 0.75 L.min^{-1} air flow rate (Fig. 20 (b) and (d)). Previous research on convective drying of food materials can help exlpain this trend where it has been found that increasing the mass loading density can lead to the creation of 'preferrential air pathways'. The chanelling of air increases the resistance for mass transfer from the drying media and results in sub–optimal drying. Both, Wang and Xi (2005) as well as Cárcel et al. (2011) have reported similar findings on the influence of mass load density during convective drying.

Lastly, urine loading displays a singificant positive correlation (R^2 = 0.81, P < 0.005) to drying rate. For a fixed ash loading to the drying chamber, increasing the urine loading increases two fundamental aspects: (i) it increases the moisture content of the ash which increases the driving force to overcome the mass transfer resistance; and (ii) it reduces the voidage in the drying media (ash). It can be presumed that a drying media with large fraction of its volume occupied by voids would be more prone to heat and mass transfer resistance. Hence to have large drying rates, the voidage fraction should be minimal; this in turn would suggest a high urine to ash loading ratio (Fig. 21).

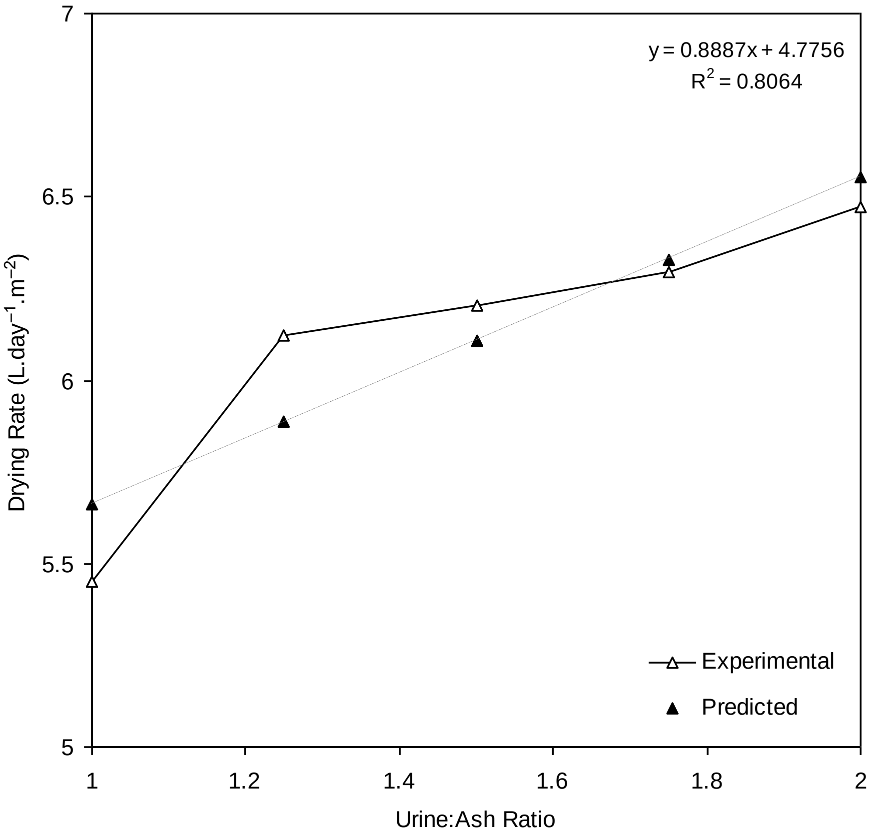


Fig. 21: Effect of urine to ash ratio (or voidage) on the observed drying rate ($P < 0.005$)

The approximate water content in human urine is 97% ; while the thermal conductivity of water at 20°C is 0.6 $W.m^{-1}.K^{-1}$, the conductivity of human urine is 0.56 $W.m^{-1}.K^{-1}$ making it one of the most conductive biological fluids (Poppendiek et al. 1967). Likewise, the thermal conductivity of wood ash varies from 0.035 to 0.048 $W.m^{-1}.K^{-1}$. This reaffirms that, for high heat and mass transfer and consequently, large drying rates, urine loading should be high while ash loading should be low. The same trend was observed in the present study which has been captured well in Fig. 20 (f).

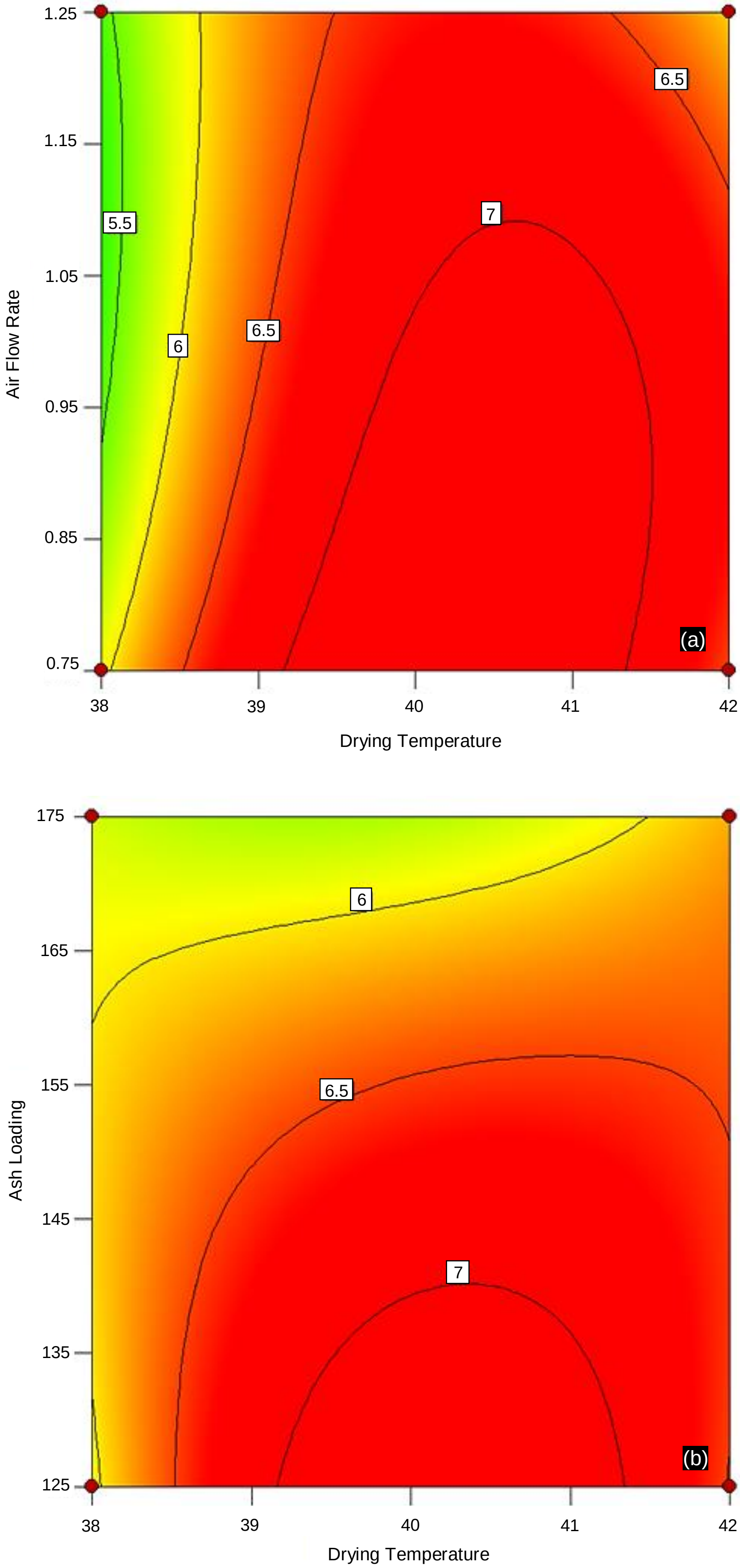
3.4.3. Numerical optimisation: identifying optimal drying conditions

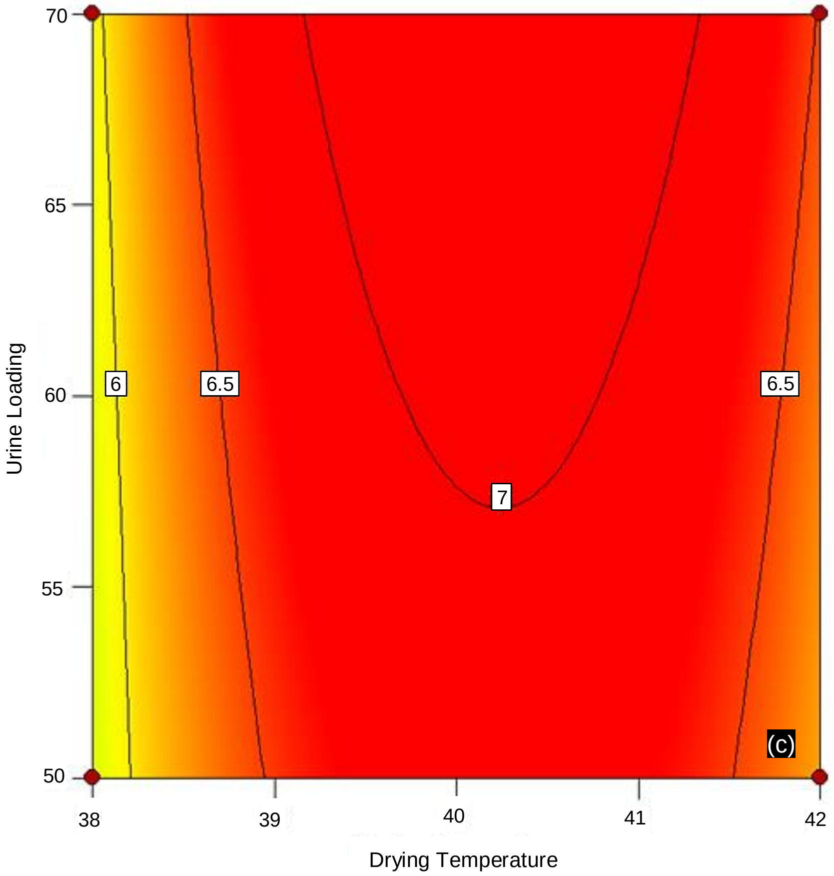
Numerical optimisation was performed according to the constraints mentioned in Table 12 (a). The RSM approach yeilded several optimal operating conditions but solution # 1 was chosen due to its high desirability (0.92) as well as due to minimal and insignificant difference between solution # 1 and the rest (Erbay and Icier 2009). The optimal conditions were found to be: drying temerature of 41.38°C, air flow rate of 0.5 $L.min^{-1}$, ash loading of 100 g and urine loading of ~ 80 mL resulting in a drying rate of 6.68 $L.day^{-1}.m^{-2}$ (Table 12 (b)). It is acknowledged and understood that the optimal solutions are valid only within the range of input variables investigated.

Table 12 (a): Constraints and inputs for mapping of optimal response				
Variable/Response	Goal	Lower Limit	Upper Limit	Importance
X_1: Drying Temperature	maximise	36	44	3
X_2: Outlet Air Flow	minimise	0.5	1.5	2
X_3: Ash Loading	minimise	100	200	4
X_4: Urine Loading	maximise	40	80	1
Y : Drying Rate	maximise	6.600	6.685	5

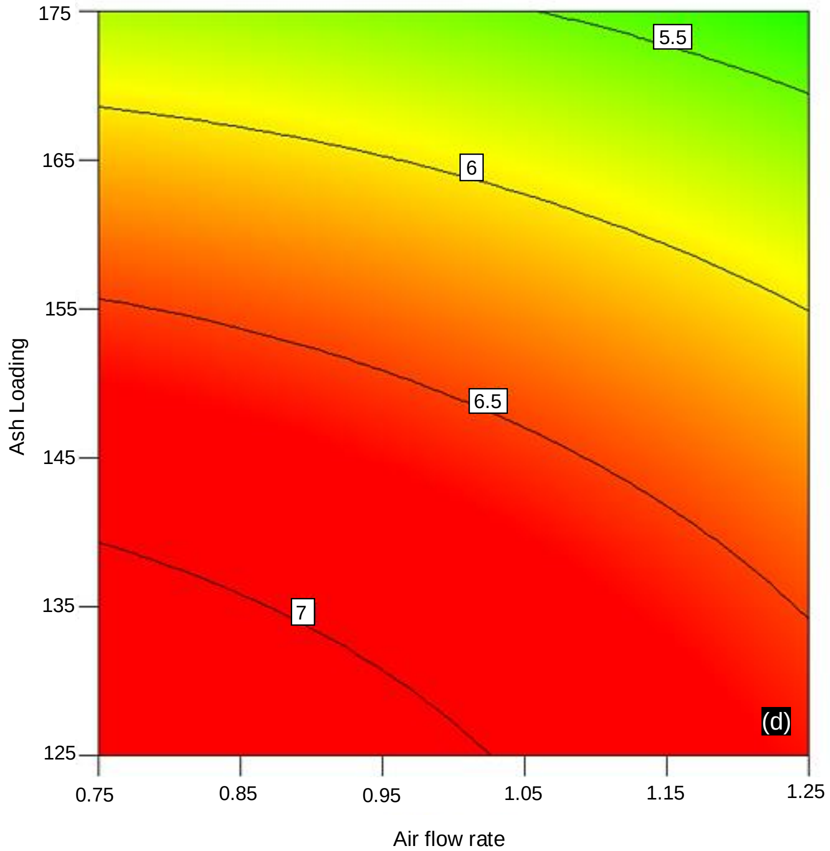
Table 12 (b): Numerical optimal solutions and their corresponding desirability functions (*di*)						
#	Temperature	Air Flow Rate	Ash Loading	Urine Loading	Drying Rate	*di*
1	**41.3826**	**0.5000**	**100.00027**	**79.95831**	**6.68502**	**0.92374**
2	41.3790	0.50000	100.00011	79.99916	6.69253	0.92368
3	41.3836	0.50001	100.12082	79.99966	6.68502	0.92354
4	41.3797	0.50000	100.00003	79.80434	6.68501	0.92340
5	41.3692	0.50000	100.00016	79.99556	6.70913	0.92334
6	41.4120	0.51518	100.00010	79.99966	6.68500	0.92293

RSM was found to be an effective tool to identify the optimal values of the input variables to the drying unit and maximise the urine drying rate. Alternatively, it is also possible to arrive at a numerical solution that minimises the loss of N during drying. A drying unit can therefore be designed and tailored based on the principle objectives it tries to address. For instance, in this study, the drying time was given a priority which resulted in a high rate (6.7 $L.day^{-1}.m^{-2}$), and yet, provided complete P and K recovery and > 75% N retention in the drying media.


1.25
1.15
1.05
0.95
0.85
0.75
Air Flow Rate
5.5
6
6.5
7
6.5
(a)
38
39
40
41
42
Drying Temperature
175
165
155
145
135
125
Ash Loading
6
6.5
7
(b)
38
39
40
41
42
Drying Temperature



70
65
60
55
50
Urine Loading
6
6.5
7
6.5
(c)
38
39
40
41
42
Drying Temperature



175
165
155
145
135
125
Ash Loading
5.5
6
6.5
7
(d)
0.75
0.85
0.95
1.05
1.15
1.25
Air flow rate

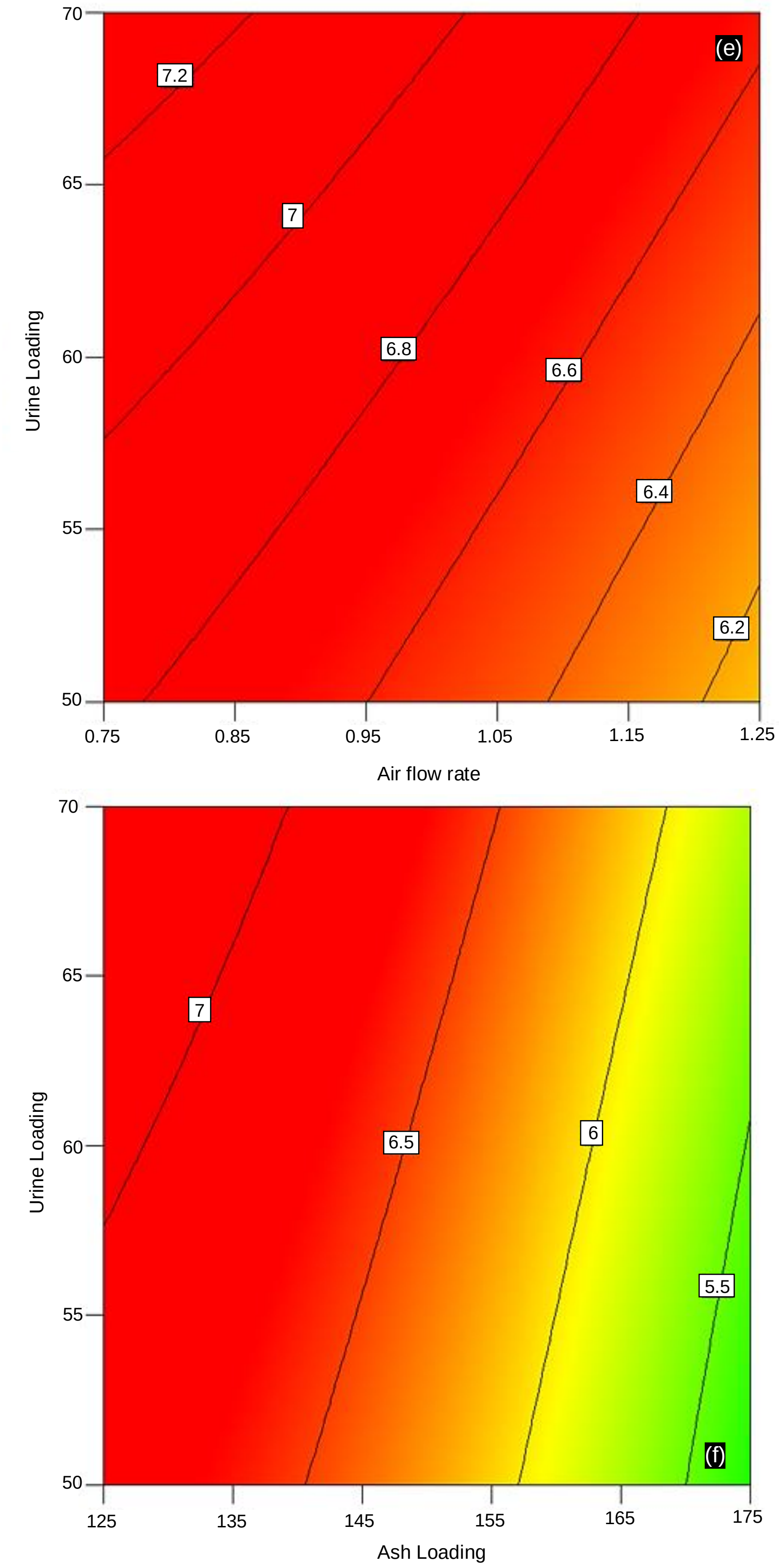
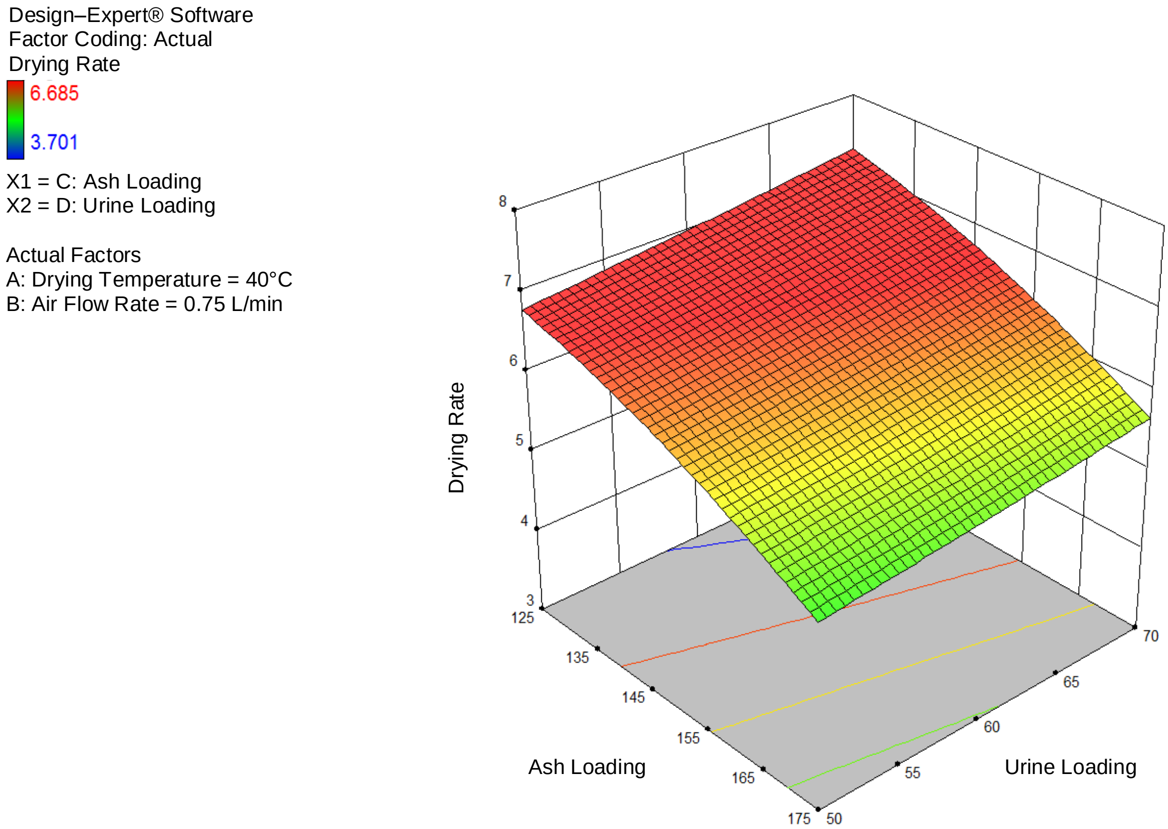
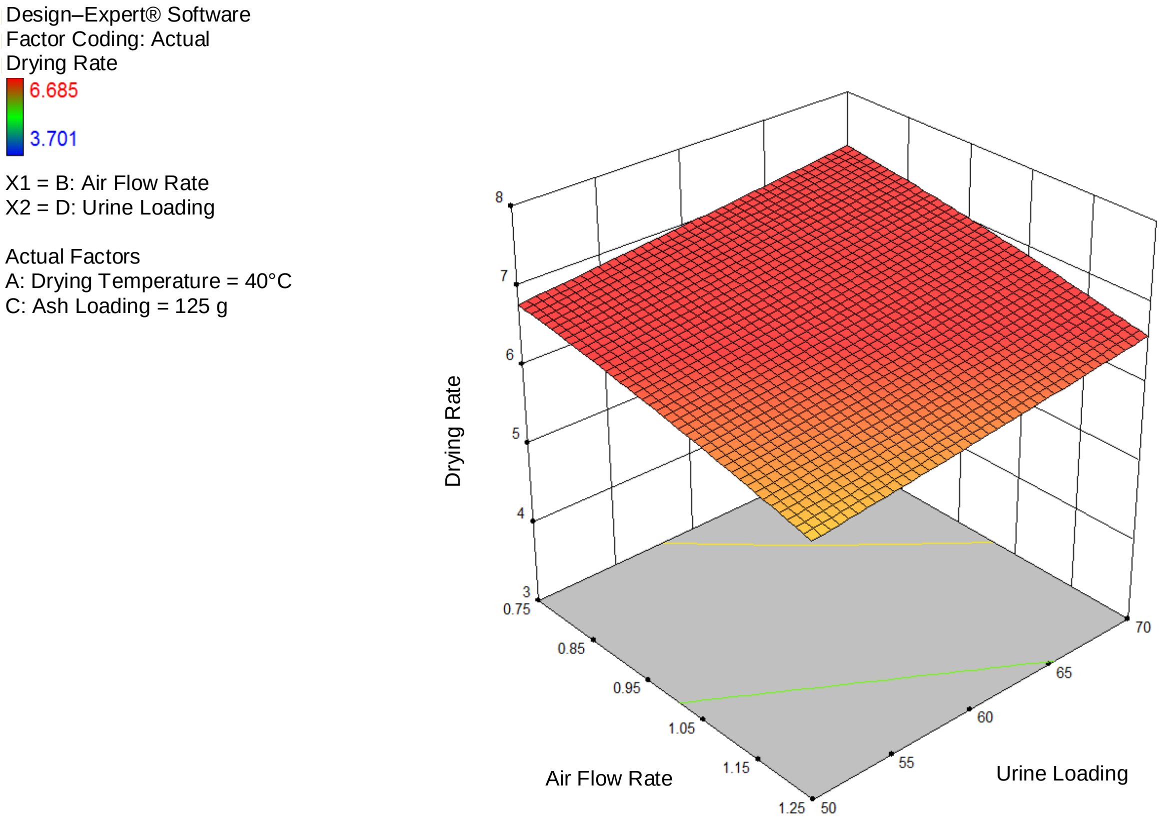
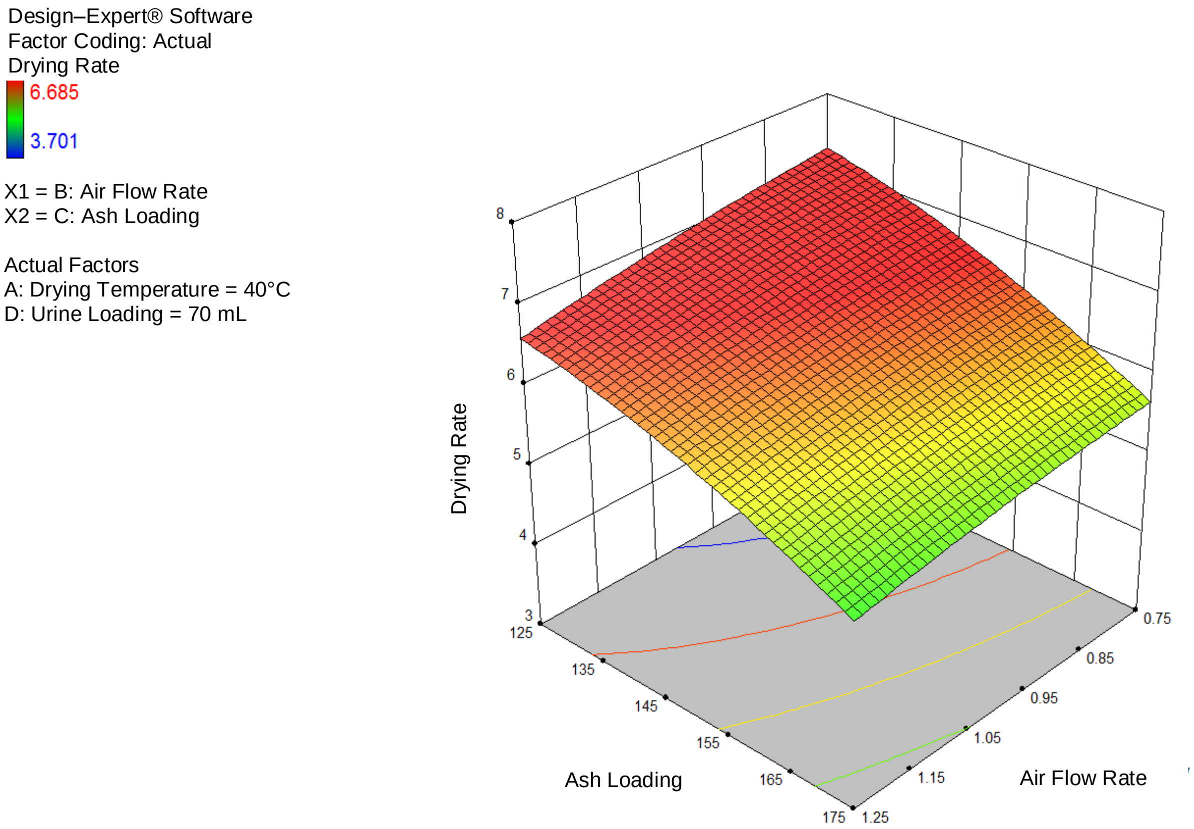
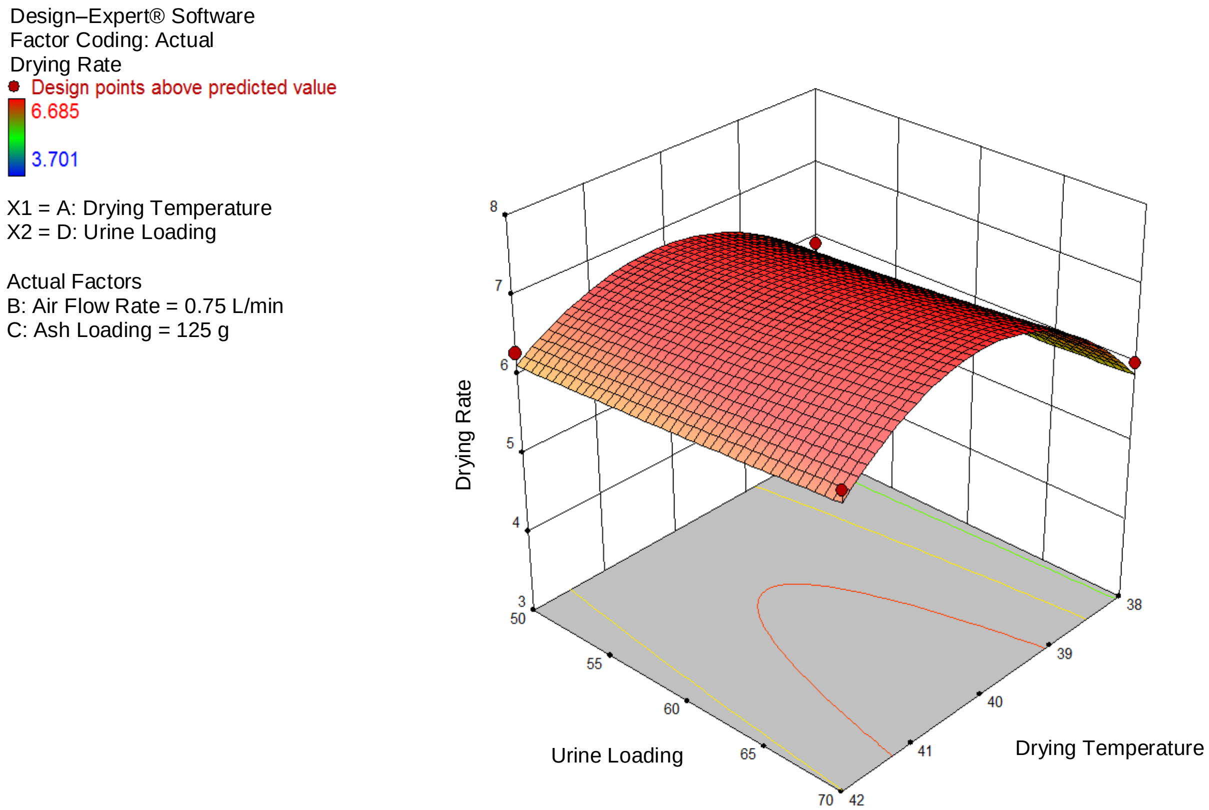


Fig. 20: 2–D Contour plots illustrating the interaction of different controlled input variables on the drying rate


Design–Expert® Software
Factor Coding: Actual
Drying Rate
6.685
3.701
X1 = C: Ash Loading
X2 = D: Urine Loading
Actual Factors
A: Drying Temperature = 40°C
B: Air Flow Rate = 0.75 L/min
Drying Rate
8
7
6
5
4
3
Ash Loading
125
135
145
155
165
175
Urine Loading
50
55
60
65
70


Design–Expert® Software
Factor Coding: Actual
Drying Rate
6.685
3.701
X1 = B: Air Flow Rate
X2 = D: Urine Loading
Actual Factors
A: Drying Temperature = 40°C
C: Ash Loading = 125 g
Drying Rate
8
7
6
5
4
3
Air Flow Rate
0.75
0.85
0.95
1.05
1.15
1.25
Urine Loading
50
55
60
65
70


Design–Expert® Software
Factor Coding: Actual
Drying Rate
6.685
3.701
X1 = B: Air Flow Rate
X2 = C: Ash Loading
Actual Factors
A: Drying Temperature = 40°C
D: Urine Loading = 70 mL
Drying Rate
Ash Loading
Air Flow Rate


Design–Expert® Software
Factor Coding: Actual
Drying Rate
Design points above predicted value
6.685
3.701
X1 = A: Drying Temperature
X2 = D: Urine Loading
Actual Factors
B: Air Flow Rate = 0.75 L/min
C: Ash Loading = 125 g
Drying Rate
Urine Loading
Drying Temperature

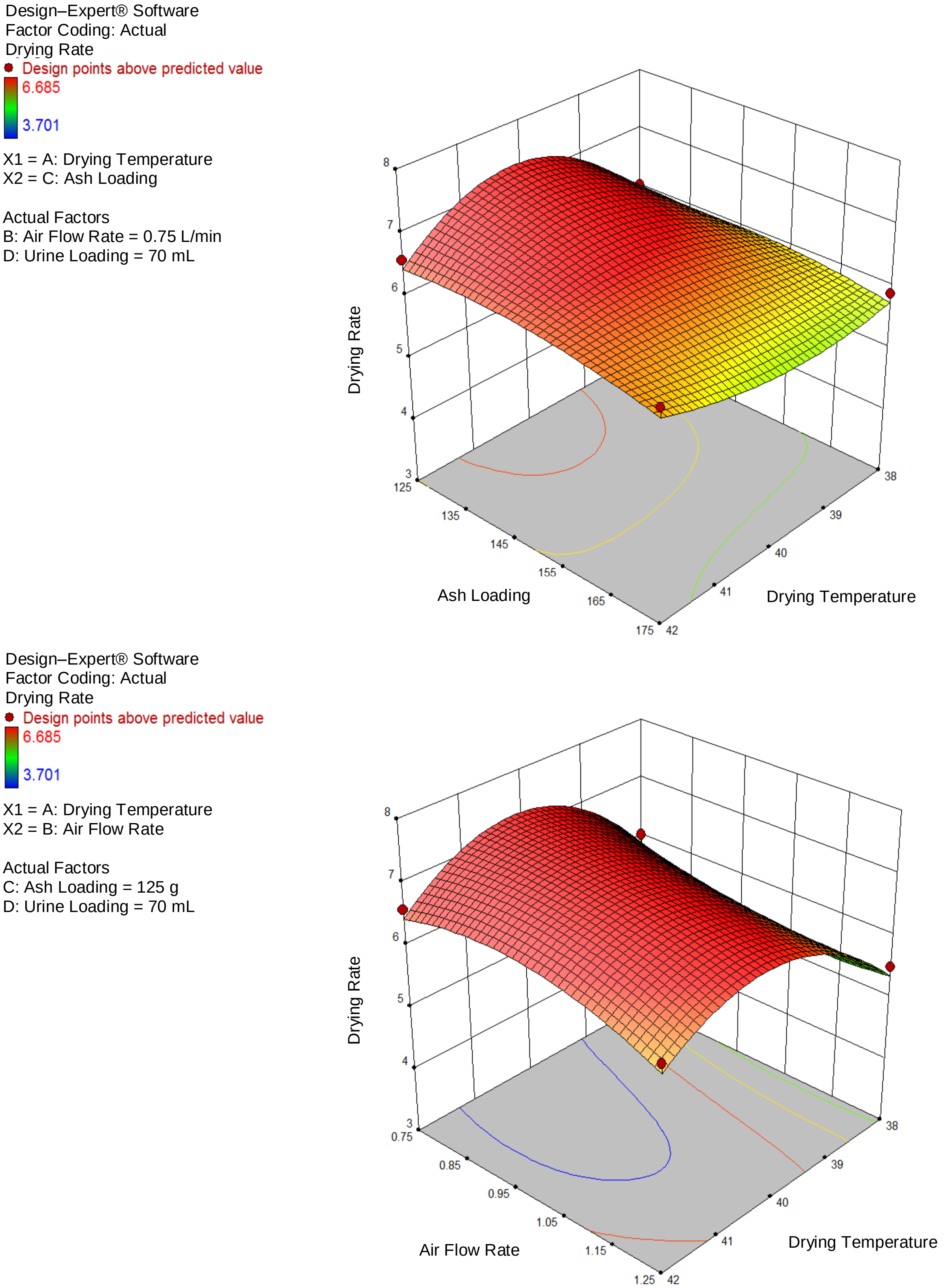


Fig. 22: Response surface plots (3–D) showing the effects of variables (X_1: drying temperature, °C; X_2: air flow rate; X_3: ash loading, g; and X_4: urine loading, mL) on the response (Y: drying rate)

3.5. Urine drying: the bigger picture

As demonstrated in the present study, the combined application of anion–exchange (as an alkalinisation pre–treatment) and passive drying (as alkaline dehydration) certainly offers an exciting and elegant approach to concentrate the nutrients in urine and enable the re–circulation of human wastes. By retaining the nutrients within an alkaline media, a drying unit keeps away all the intrinsic N, P and K in urine from entering the water system which as of now accounts for 80% of the nutrient load in a conventional WWTP.

The salient advantage of the system put forward in this study is volume minimisation. While there are other technologies that offer similar nutrient recovery potential such as struvite precipitation (and NH_3 adsorption), nitrification, $Ca(OH)_2$ stabilisation, etc. they still require channelling substantial amounts of stabilised urine or treated wastewater from the source to agricultural areas (sink). An added benefit of utilising the anion–exchange resin for stabilisation is that it strips the Cl^- ions from urine thereby effectively eliminating any possibility of increased soil salinity from the reapplication of the dried urine mixture.

As stated earlier, the objective in the present study was to gauge, in isolation, whether the combination of anion exchange and passive drying could be an effective approach for preserving, concentrating and recovering nutrients from urine. However, the long–term objective was to provide results that contribute towards the design and development of a new toilet.

Fig. 23 provides a (tentative) conceptual approach that integrates the two investigated processes with a urine diversion dry toilet. Here, the ion–exchange resin is perceived as being part of the urine diversion bowl where it provides the necessary elevation of pH to facilitate the stabilisation of urine during storage. Certainly, an important design consideration will be to identify the best procedure of packing the resin beads so as to ease its retrofitting into the bowl, allow at least 75% of the urine to pass through it and be easy enough for users to replace and regenerate.

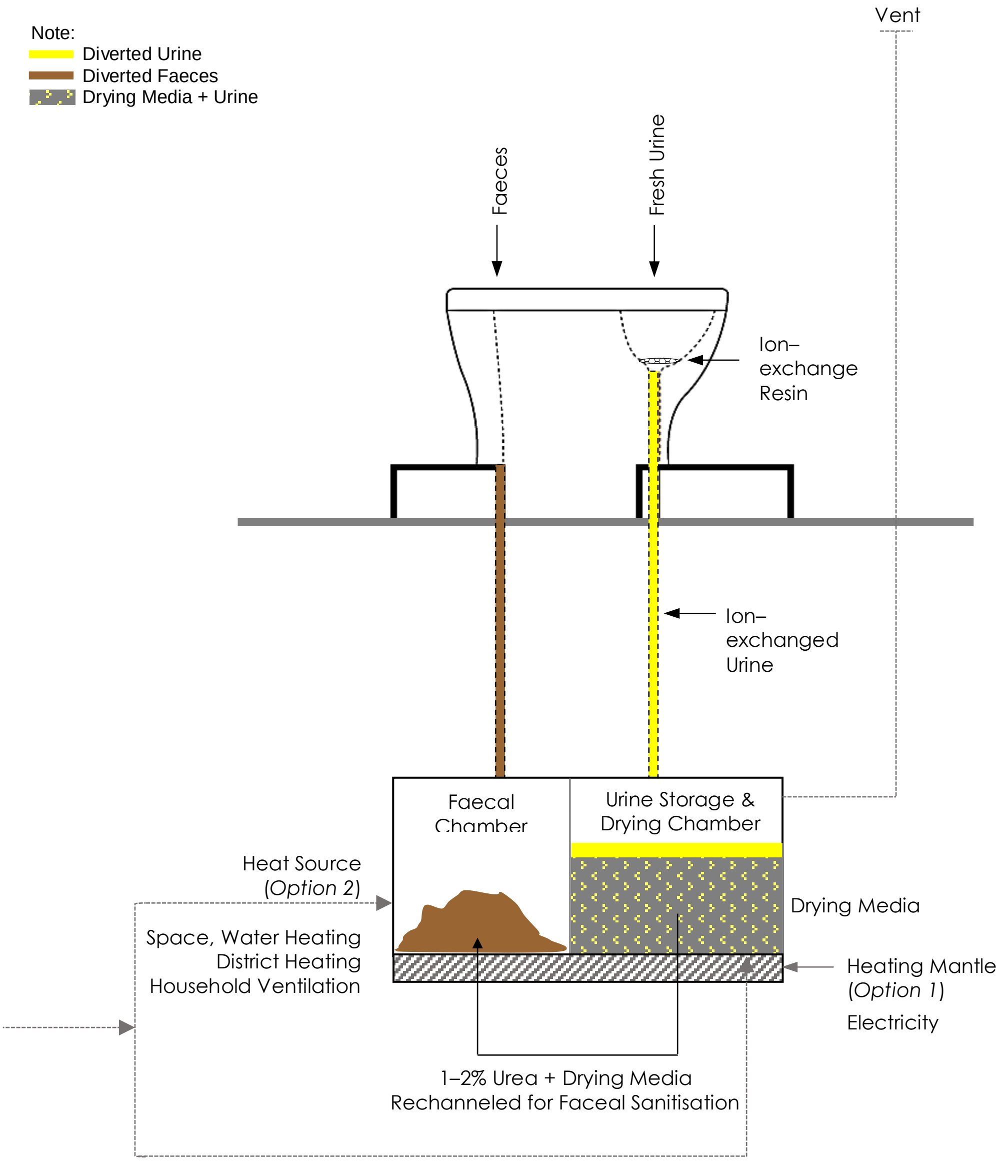


Fig. 23: A new toilet design – integrating anion–exchange and alkaline dehydration with UDTs; *Illustration by Author* §

Further, based on a user preference of the mode of drying, it would be possible to have either a urine storage chamber or a urine drying chamber. For individual, self–operated toilets (decentralized sanitation) urine can be directly channelled to a drying chamber containing a

§ Basic schematic of Urine Diversion Dry Toilet adopted from Tilley et al. (2014) and modified to fit the purpose pre–determined quantity of the drying media. The heat energy required for performing the drying can either be sourced as standalone or a combination of the following:

a. Electricity (preferably renewable) supplied through a heating mantle;

b. Waste or leftover energy available from the space heating or water heating; this would an ideal choice for households in colder climate and during winter.

With respect to source–separated faeces, the addition of an alkali (ash, lime) would be favourable as pH elevation (≥ 12) results in pathogen inactivation following a storage period of 3 months. However, for the present system, 'ammonia sanitisation' offers a more feasible approach to faecal management. While the aim in urine drying is to stabilise and preserve urea–N by preventing its hydrolysis, ammonia sanitisation takes advantage of the decomposition of urea by hydrolysis into NH_3 and ionic CO_3^{2-}, which in turn cause disinfection (Nordin et al. 2009). Nordin (2010) also notes that addition of 1% urea (w/w) in combination with ash (0.1 L per 100 g faeces) results in a 2 $\log_{10}$ reduction of *Ascaris* eggs within 5 days at 34°C. Hence, transferring a portion of the dried mixture of urine and ash (or any other drying media) from the drying chamber to the faecal chamber provides a simple yet, effective approach for the safe reutilisation of faeces and further value creation by harnessing the nutrient concentrations therein.

Fig. 24 presents a semi–decentralized (or semi–centralized) sanitation system as an alternative to the one discussed earlier in Fig. 23. While there is no change in the conceptual approach towards waste management, the advantage here lies in the ability of the system to provide a central facility for collection, storage and treatment. Semi–centralization could also make room for better process control of the variables influencing the drying as well as for monitoring the pathogen inactivation to ensure sufficient hygienisation has occurred. Moreover, the quantities of recovered nutrients in such a system would be significant enough to justify the logistics in transferring them to agricultural areas for use as fertilisers.

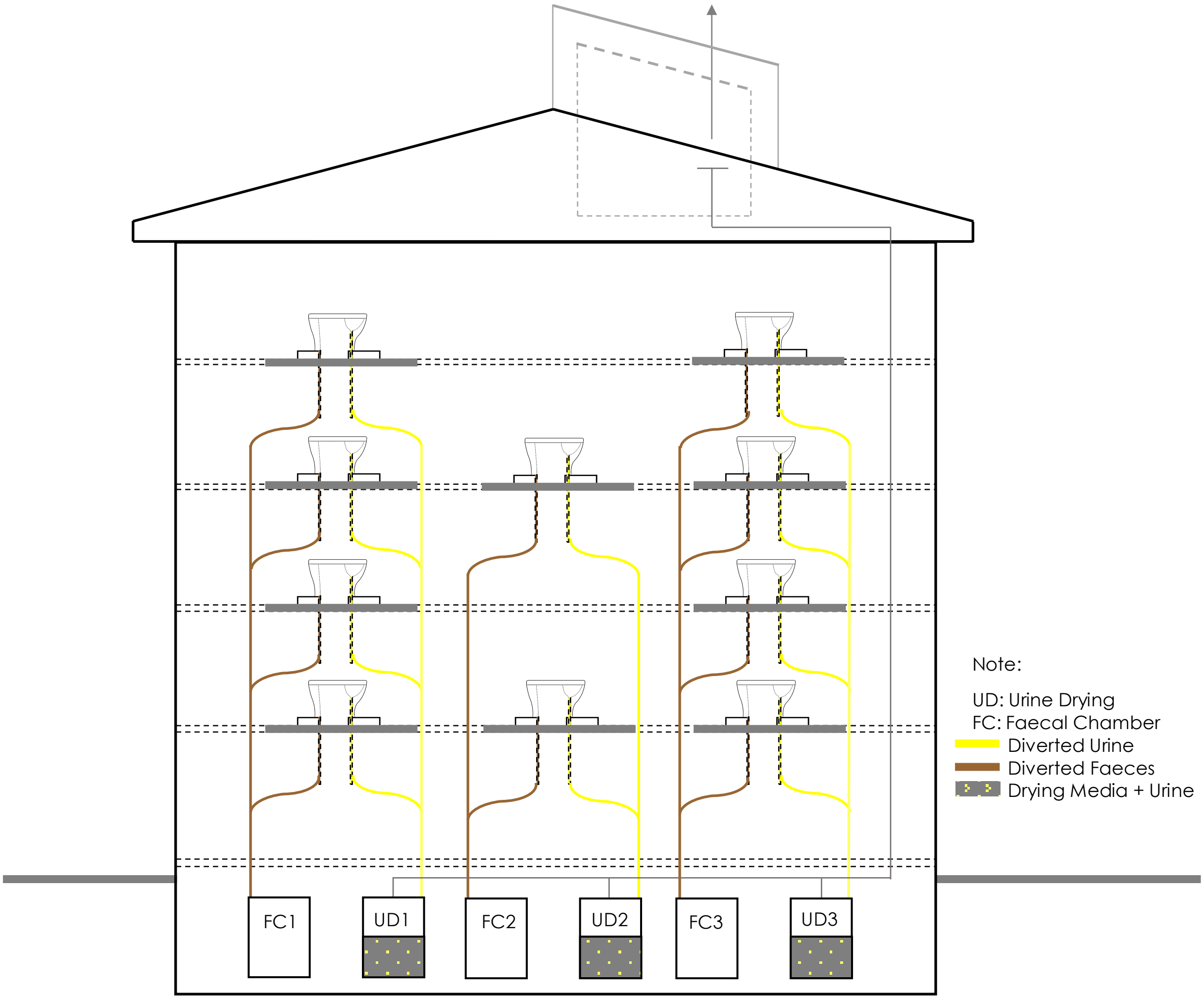


Fig. 24: A semi–decentralized approach for integrating anion–exchange and alkaline dehydration with UDTs; *Illustration by Author*

Lastly, in an effort to '*fit and conform*' the approaches put forward in this study with current systems and result in their immediate adoption, an alternative that uses urine diversion flush toilets has been suggested (Fig. 25). Since both their appearance as well as operation is very similar to conventional cistern–type flush toilets, their use in combination with a drying unit could be perceived as a first step towards the wider adoption and proliferation of urine drying in sanitation.

In conclusion, it is acknowledged that incorporating the two processes investigated in the present study into a urine diversion dry toilet will be challenge in system design. In any case, it will be imperative to ensure that any design put forward be simple, entail low initial investment and operating costs, require minimal changes in user practices, be easy to maintain and clean (preferably using material readily/usually available in households) while extending all the necessary and expected benefits of sanitation and hygiene.

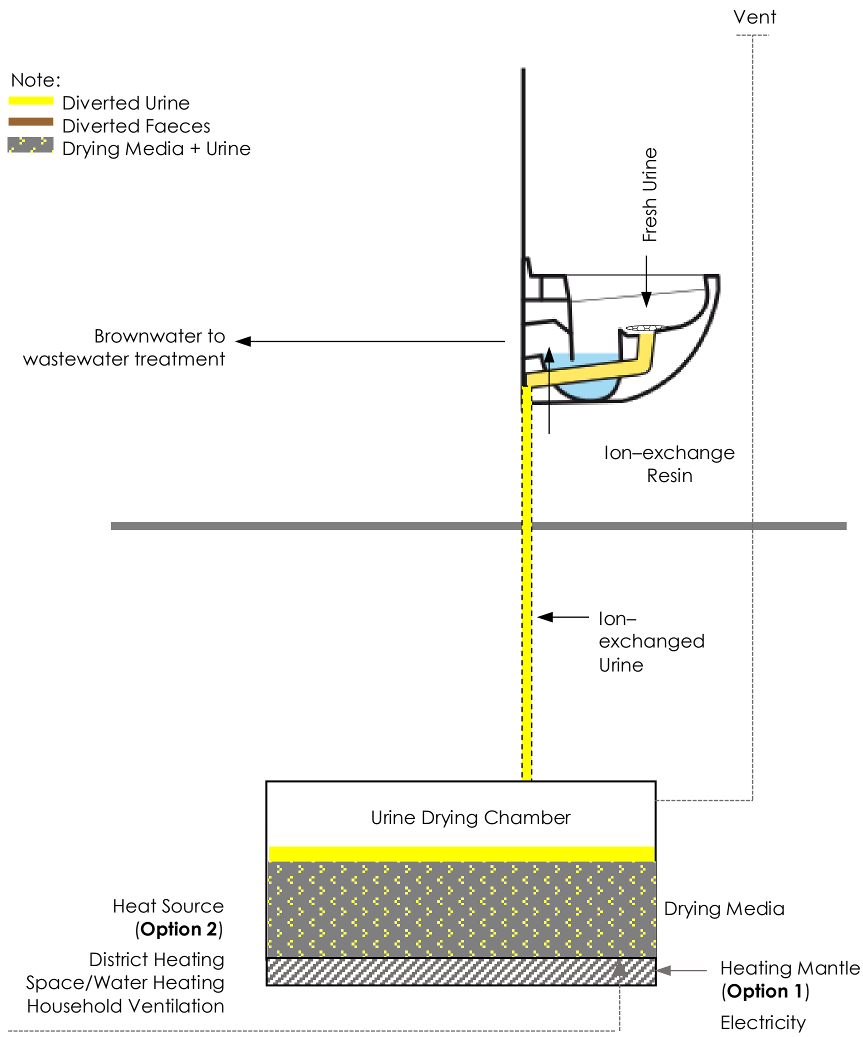


Fig. 25: A '*fit and conform*' approach for immediate adoption of urine drying; *Illustration by Author*

3.6. Analysis of farmer attitudes towards human waste recycling

Coming from a sociological perspective, the remaining sections of this study provide insights from farmer surveys conducted in South India over producer perspectives, attitudes, and willingness to use human excreta in agriculture. The objective in administering these surveys was to note the current level of knowledge of waste recycling among farmers, gauge its potential level of acceptance, and identify the factors that encourage or discourage its adoption.

3.6.1. Initial screening and sample socio–demography

A total of 62 out of the 120 cultivators approached in this study completed the entire survey (response rate = 52%). Of these, 98 cultivators provided responses to all questions up to question 20 (response rate = 82%); 62 answered questions 20.1 and 20.2 while 68 chose to answer questions 21 and 22 (See Appendix AX 2–6). A relatively high response rate was observed in comparison to surveys conducted elsewhere (Mariwah and Drangert 2011; Lamichhane and Babcock 2013; Ishii and Boyer 2016) partly due to the survey being administered through face–to–face interviews. It was interesting to note that many of the cultivators were pleasantly surprised with the surveyor's visits and their request to opinionate on soil fertilisation with human wastes. The continued neglect of smallholder agriculture in governmental schemes and outreach programs, especially in terms of access to, and quality of public goods and services can perhaps explain this (NCEUS 2008); 87% of the respondents owned < 4 ha of farmland.

Of the 98 respondents, there were 80 male and 18 female cultivators (Table 13). This disproportionate gender segmentation can be attributed to the rural societal structure in which men are considered heads of the household, the decision makers and have traditionally been in charge of the income generating operation of cash crop production. On the other hand, the women's role is confined to either cultivating vegetable crops for household consumption or selling a small portion of the produce at the local farmer's markets (Rengasamy et al. 2002, p. 27). Majority (78%) of the cultivators have been on their farms for more than 6 years with 72% of the farms being home to 3–6 people. Less than 7% of the cultivators belonged to the age category of < 30 years; this is concurrent with the on–going demographic crisis in Indian agriculture in which young people have been increasingly less inclined to look towards agriculture for livelihood (Sharma 2007; Rajan 2013).

Income levels were found to be predominantly low and low to medium (< ₹100,000 or approximately, US$ 1560 per annum as per 2015 currency exchange rates). The incomes correspond well with the size of the land holdings; 75% of the farmers with low income and 67% of the medium income farmers cultivated on < 2 ha.

A significant proportion of the farmers (27%) did not wish to disclose their annual income. Of these, 73% stated that their farm size was < 2 ha while 15% owned more than 4 ha. The hesitation to disclose their incomes can either be because their income levels were probably low and low to medium (among the former) or that they had high incomes (in the latter). All except one cultivator stated that they followed Hinduism and this proportion is representative of the religious demographics in Tamil Nadu.

In Tamil Nadu, 'caste traditionalism' plays an important role in determining people's profession; traditionally, the upper castes were 'land–owners' who never worked on the farm as manual labour was considered demeaning and best left to the lower castes (Deliege 1992; Fuller and Narasimhan 2014). Over the years, the upper castes migrated to the cities and sold their rural landholdings, while the lower castes transformed their identities to become 'authentic agriculturalists' (Fuller and Narasimhan 2014). It is therefore not surprising to see less than 9% cultivators belong to the upper caste whereas the Other Backward Classes (OBCs), Scheduled Castes (SCs) and Scheduled Tribes (STs) account for 83% of the respondents. The OBCs also account for 75% of all the landholdings with size < 1 ha.

Table 13: Socio–economic and cultural characteristics of the survey respondents			
Demographic Data	**Abbreviation** [1]	***N***	**% of tot–*N*** [2]
Gender			
Male	m	80	82
Female	f	18	18
Age			
< 30	young	7	7
30 – 45	young_medium	27	28
45 – 60	medium_old	40	41
> 60	old	24	24
Family Size			
≤ 3	a	14	14
3 – 4	b	32	33
4 – 6	c	39	40
> 6	d	13	13
Religion			
Hindu	hin	97	99
Muslim	mus	1	1
Christian	chr	0	0
No Religion	nr	0	0
Do not wish to disclose	dnwd	0	0
Others	oth	0	0
Caste			
Scheduled Caste (SC)	sc	11	11
Scheduled Tribe (ST)	st	4	4
Other Backward Caste (OBC)	obc	67	68
Upper Caste (UC)	uc	9	9
Do not know	na	1	1
Do not wish to disclose	dnwd	6	6
Annual Income			
≤ 45000 ₹	l	39	40
45,000 – 100,000 ₹	m	30	31
> 100,000 ₹	h	3	3
Do not wish to disclose	na	26	27
Farm Time			
≤ 3	early	5	5
3 – 4	early_med	12	12
4 – 6	med_long	1	1
> 6	long	62	63

[1] abbreviation used in subsequent graphical illustrations; [2] % may add up to > 100 due to rounding

Section II of the questionnaire elicited information about the type and nature of farming in Vellore as well as the farmer's perception of his/her fertiliser requirements. There is diversity in the types of crops cultivated and includes rice, sugarcane, coconut, groundnut, vegetables, maize and black gram. Although 35 farms followed monoculture cropping, 28 followed multiple cropping and a further 17 practiced crop rotation. Moreover, 13% of the farmers considered themselves as 'purely organic' with the majority (60%) considering themselves as organic apart from the use of chemical pesticides. In terms of fertiliser use, 74% state their requirements as being small and small to medium. As is the practice in most Indian farms, 95% of all the respondents used animal manure for fertilising their soils.

3.6.2. Is there a difference between cow urine and human urine?

Historically, the cow has been considered holy in the Hindu religion, extensively studied and used in the ancient system of Indian medicine and routinely finds use as a 'safe' crop fertiliser. Conversely, most if not all activities that deal with human urine, sanitation, cleaning and maintenance of sewers and toilets are considered 'polluting labour'. This follows from the customary and intertwined caste–based system in the Indian society wherein, 'polluting labour' is designated to communities (*Dalits*) whose castes are also considered 'polluted' or 'untouchable' (Narula 1999). In 2014, the Supreme Court of India estimated that 9.6 million dry toilets are still being manually cleaned throughout the country by people belonging to the scheduled castes (Human Rights Watch 2014). This estimation however does not take into consideration the manual scavenging of excrement from uncovered drainages or septic tanks.

With this in mind, the survey of farmer attitudes was initiated by asking the farmers if they considered human urine to be any different than cow urine in terms of its fertiliser potential. Of the 98 respondents, 52% of the farmers believe that human urine is different from cow urine (Fig. 26). A statistically significant difference (p = 0.046) was observed between the mean responses of the male and female cultivators with 72% of the female cultivators considering human urine to be no different than cow urine. Also, in terms of their caste affiliations, scheduled tribes (μ = 2) and scheduled castes (μ = 1.64) cultivators believe that the two urines are different while the upper castes (μ = 1.33) do not. Although mean responses when compared against annual income was found not to be significant (p = 0.111), it is interesting to see that the feeling of human urine being different than cow urine decreases with increase in income. The size of the landholdings also influenced (p = 0.007) the farmer's opinion depicting a trend similar to that of their incomes.

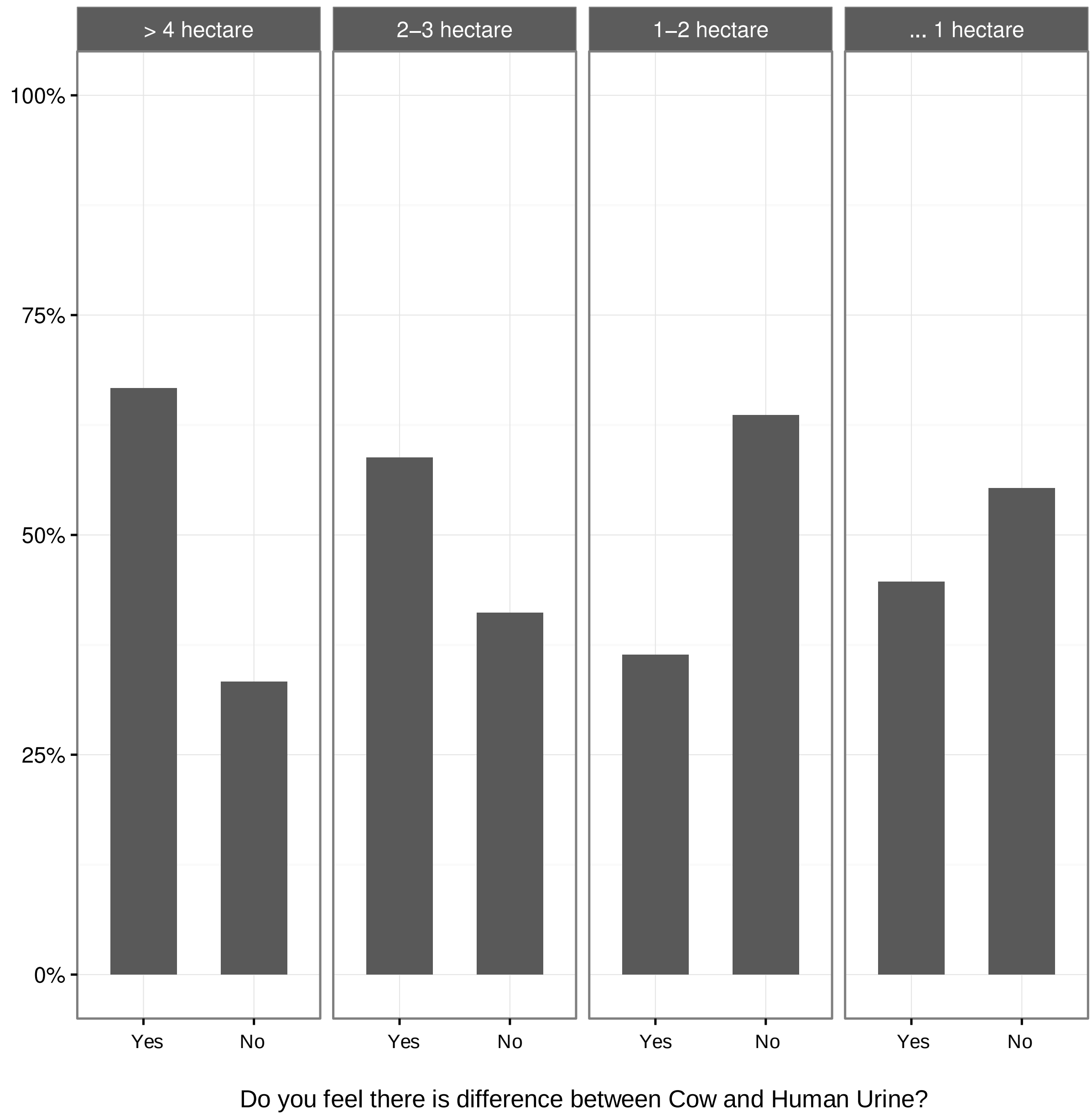


Fig. 26: Graphical representation on the respondents' views on whether there is any difference between human and cow urine in terms of fertiliser potential ($P < 0.05$); responses are separated into the landholding size (>4 ha, 2–3 ha, 1–2 ha, ≤1 ha) of the respondents

3.6.3. *Not–in–my–circle syndrome*

A majority of the respondents (82%) did not know anyone else that uses or used human urine for crop fertilisation. No statistical difference between the mean responses was found against all demographic variables except family size. None of the farmers who have stayed on their lands for less than 6 years knew anyone who had used human urine while all those who did know someone have spent at least 6 years on their farms. Further, none of the scheduled tribe or scheduled caste farmers knew anyone using human urine. Nonetheless, most of the farmers who did know someone using human urine as a fertiliser considered themselves as organic farmers (83%).

The motive in question 17 was to understand if the farmers would feel differently if someone they knew or were related to, started using human urine as against if their neighbour started using it. Surprisingly, 92% of the farmers stated they would feel negatively if someone they knew started using urine as a fertiliser whereas, only 41% responded negatively to their neighbours using it (Fig. 27). This trend is quite similar to people's sentiments that is captured by the NIMBY (Not–In–My–BackYard) syndrome that has been used to describe situations in which development projects have been met with resistance due to their spatial proximity to people's homes and their potential to disrupt people's routines, behaviour and way of life (Dear 1992).

In this case, we have what appears to be a *not–in–my–circle* syndrome as farmers would rather see their neighbours use human urine than their friends, family and colleagues. However, even among the farmers with a positive attitude, some did remark that they do not mind their neighbour using urine as long as no foul odour finds its way to them; if this happens, they would be forced to object and take issue against their neighbours. An economic motivation to use urine was evident among a few farmers who stated that, if their neighbours used human urine and received good productivity gains from it, they too would give it a try since it is a 'free fertiliser'. Based on the type of farming, responses of organic and inorganic farmers differed significantly (p = 0.042); respondents identifying themselves as organic farmers would not mind their neighbour using urine while the ones identifying themselves as inorganic would.

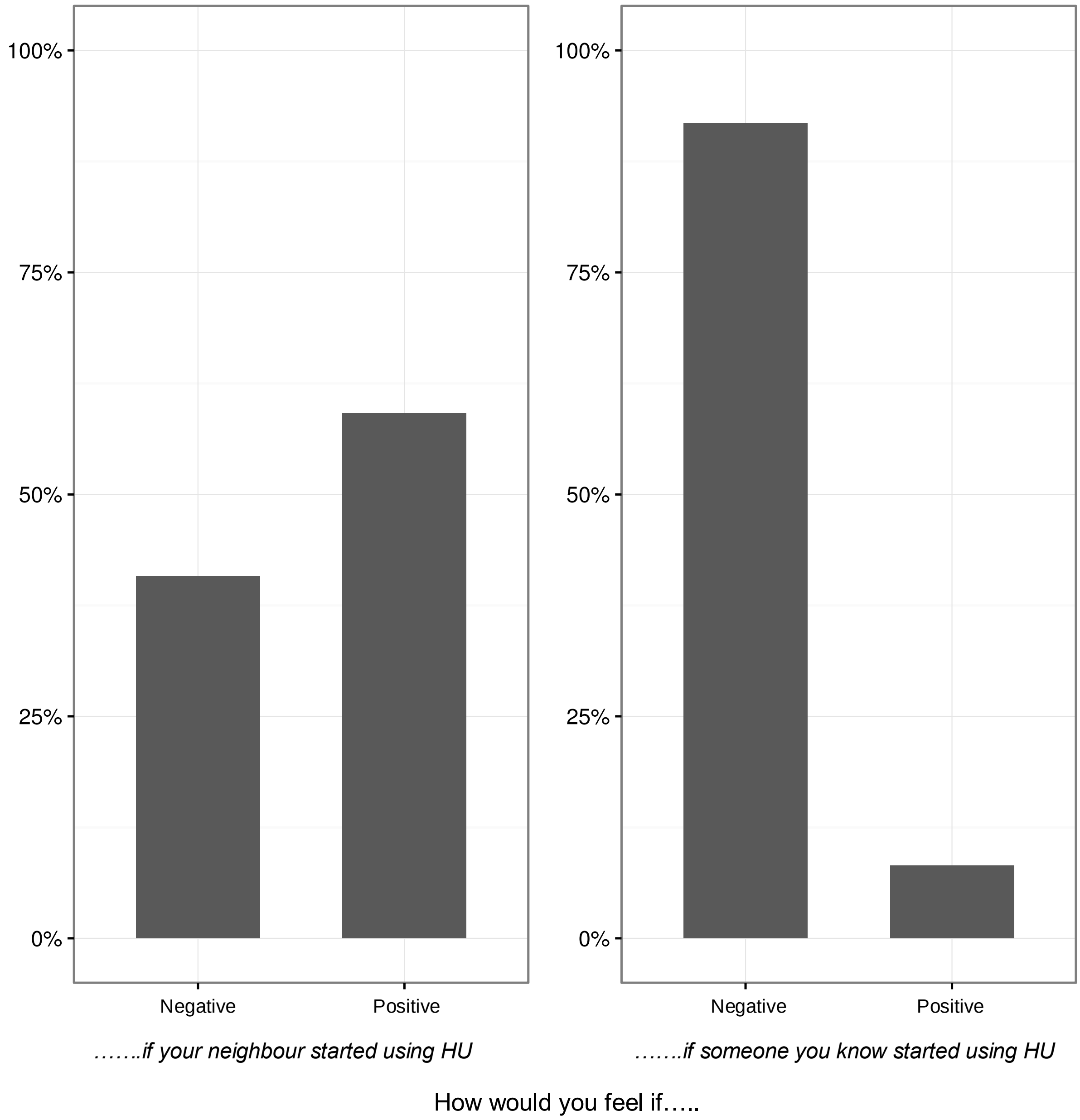


Fig. 27: Graphical representation of respondent attitudes on their neighbours (left panel) and someone they know (right panel) using human urine as a fertiliser; Not–in–my–circle syndrome among survey respondents in Vellore, India.

3.6.4. The consumers: market place dynamics

The farmers were subsequently asked to provide an opinion on whether they thought people in the market place would be willing to buy food produced on a farm that used human urine as a fertiliser. Evaluating these responses could explain if the farmers thought any potential barriers and/or incentives existed among the consumers of their produce.

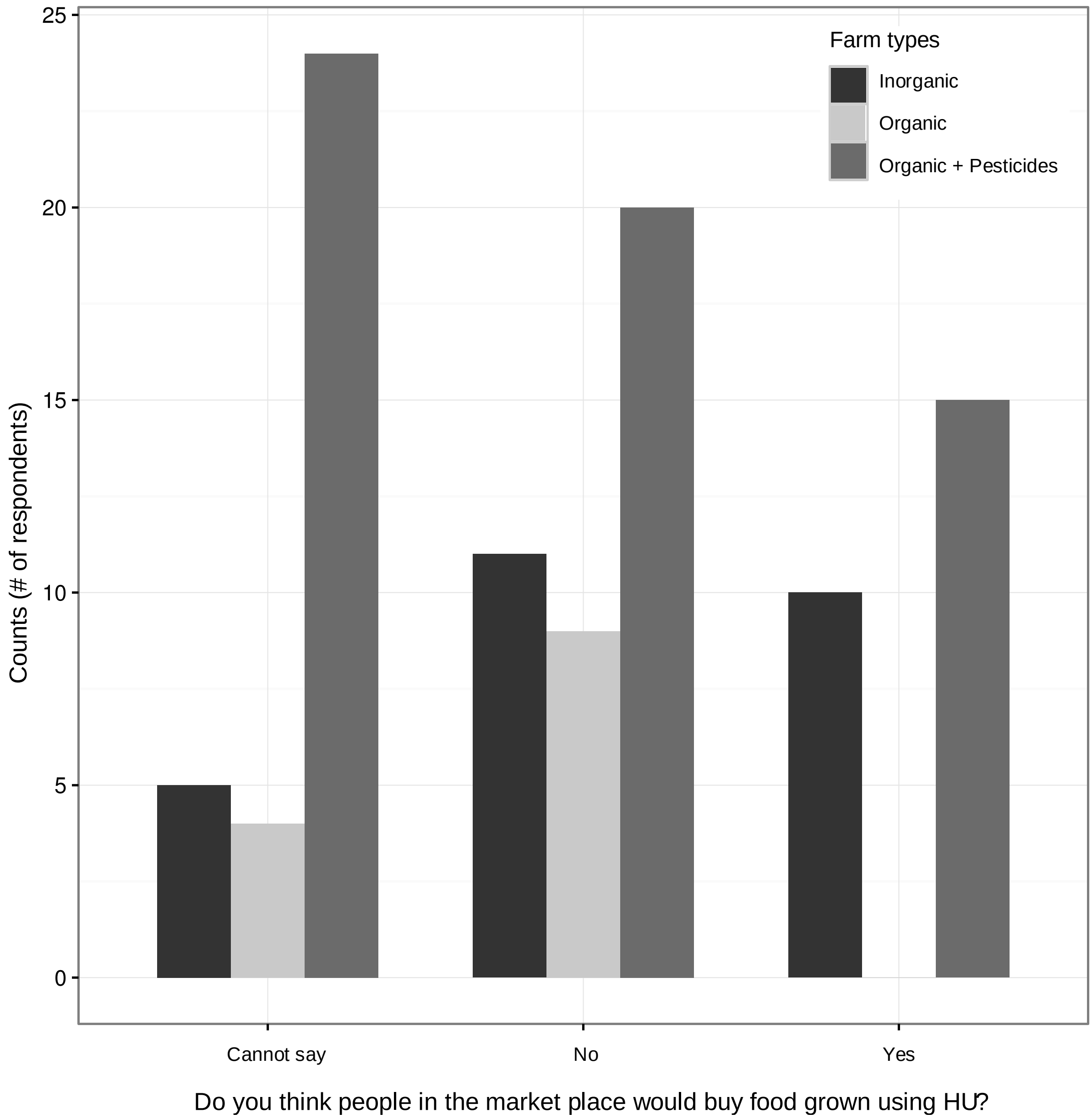


Fig. 28: Producer's views on whether people at the market would buy products fertilised with human urine, segregated as per the type of farming the respondents' identify themselves as practicing; inorganic (dark grey), organic (light grey) or organic+pesticides (medium grey)

Only 25% of the farmers stated that they thought people in the market would buy urine fertilised produce, while 34% of the farmers stated that they could not take a stance on this as they felt consumer behaviour would not be something they could predict (Fig. 28). The comments from the farmers on this question were quite interesting to note. Of those who felt that consumers would buy it felt so because (i) they would not inform their consumers in the first place; (ii) the consumers would think the farmer was lying and buy the food nonetheless; (iii) since it is urine fertilised food, it would create room for bargaining and consumers inclined to buy food at cheaper prices could be targeted by the farmer. The mean response of the inorganic farmers was found to differ significantly from the other farmers (p = 0.034). It was surprising to observe that none of the 'pure organic' cultivators thought that people in the market would buy urine fertilised food while 48% of the inorganic farmers felt otherwise.

3.6.5. Farmer perceptions and willingness to use human urine

When confronted with the question whether they thought human urine can be used as a fertiliser, of those who took a stance, 59% answered positively. At p = 0.01 level of significance, the female farmers were more positive than their male counterparts. None of the scheduled caste farmers wished to answer the question and stated they could not opinionate on it. At this point in the survey, there were clear signs of visible anger and even shyness among a few farmers all of whom belonged to the upper caste, had 2–4 ha of land and medium level of income. There were also some shrewd yet admittedly wise responses; a couple of farmers reverted by remarking that since they had little prior knowledge or information on the subject, they would rather hear our opinions.

Next, the farmers were asked if they thought it would be a good idea to use human urine to fertilise their own crops to gauge the potential level of acceptance of urine based farming. Mean responses when compared with the demographic variables were not found to differ significantly. However, with respect to age it was observed that, older the farmer, the more likely it was that he/she would use urine; most of the young farmers thought it would be a bad idea. The scheduled caste and upper caste cultivators were mostly against the idea of using urine on their own crops. A further trend was seen with respect to annual income; the lowest income farmers (μ = 1.62) were largely in favour of urine usage as against the ones with high incomes (μ = 1.33).

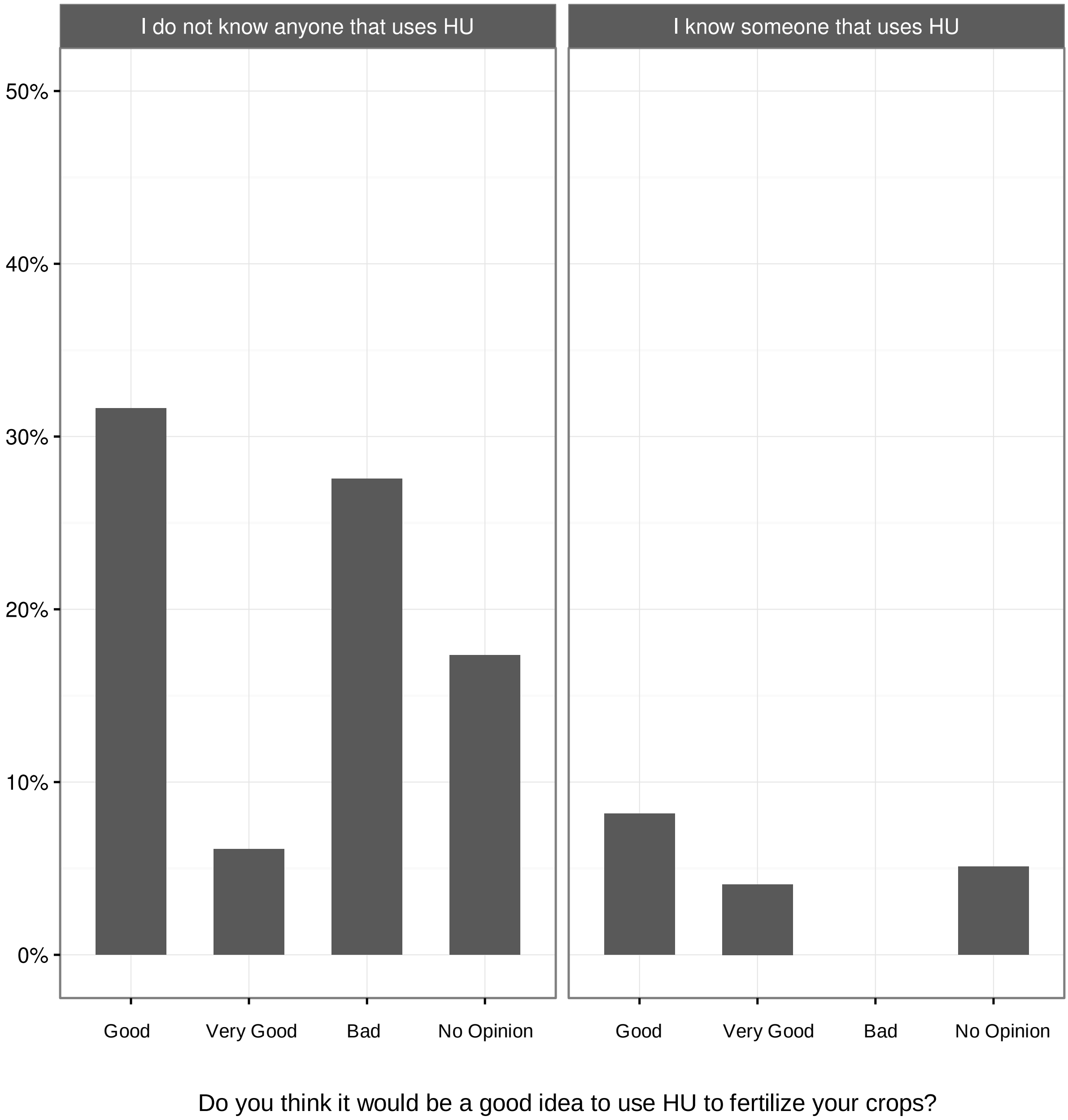


Fig. 29: Farmer attitudes/willingness to use human urine differentiated as to whether they know anyone that uses HU as fertiliser (left panel) and the ones that do know someone (right panel)

Of the ‘pure organic’ farmers that did express an opinion (N = 6), all felt that it would be a good or very good idea. Interestingly, none of the farmers who had stated earlier that they knew someone who uses (or used) human urine thought it would be a bad idea for them to use it on their own land (Fig. 29). Moreover, most of the farmers who responded ‘cannot say’ followed it up with a comment that they would have to see a demonstrated benefit in terms of crop productivity equivalent to at least that of animal manure for them to consider using human urine. Presumably, for farmers to adopt human urine as a fertiliser either they must know someone who uses (or used) it and/or must be convinced of its crop productivity potential. Many farmers also stated that they were willing to allocate a portion of land on their farm to test the fertilisation potential of urine on various crops that they usually grow if someone took the initiative to demonstrate how they could safely apply it.

3.6.6. Factors that shape positive and negative attitudes on urine recycling

Of the 98 farmers, 36 that responded to all the previous questions (questions 15–20) did not participate further. An analysis of the mean response (μ = proportion of farmers who responded to further questions) against the socio–demographic and farm characteristic variables provided some insights. All the farmers who have spent ≤ 2 years and 64% of those that have spent less than 4 years were not interested in further questions. Further, farmers with landholdings ≤ 1 ha did not participate (μ = 1.59) further while nearly all the farmers with > 4 ha did (μ = 1.88). Strangely, based on the previous questions asked of them, the inorganic farmers (μ = 1.63) were more interested in the survey as against the ‘pure organic’ farmers (μ = 1.38) and ‘organic + pesticide’ (μ = 1.43). Gender, age, income and caste provided no statistically significant difference for the responsiveness and non–responsiveness of the farmers. However, from this point in the survey, none of the ST farmers participated in further questions.

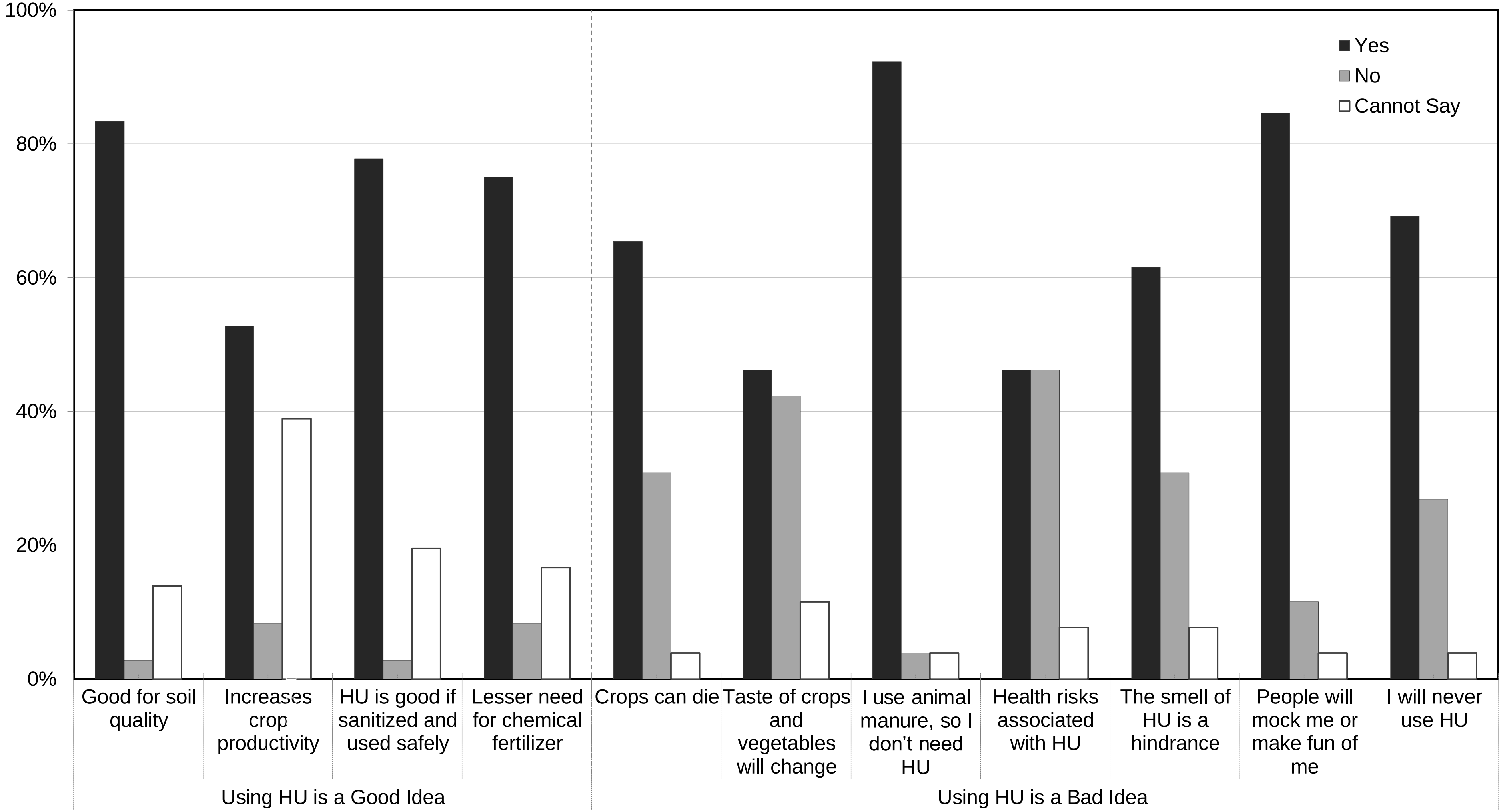
Based on farmer attitudes (positive/negative) to the previous question of using urine on their own farms, they were asked two different sets of additional questions to understand why they considered using human urine to be a good (4 statements) or bad idea (7 statements). The primary factors that motivated the farmers to respond positively towards the possibility of using human urine were soil quality and potential gains from reduced chemical fertiliser use (Fig. 30). 83% of the farmers believe that using urine would improve their soil quality while 75% were of the opinion that using urine would reduce their need for chemical fertiliser which currently adds to their cost of production. Despite little information on urine sanitisation, concentration of micro–pollutants and pharmaceuticals, 78% of the respondents considered urine to be a 'safe' fertiliser. Health risks associated with urine handling and reuse might not be of high concern to these Vellore farmers, but crop productivity certainly is; 39% of the farmers were not aware of the agronomic potential of urine as a fertiliser while an additional 8% thought crop productivity might not increase with urine but they might still use it.

There is concern about crop die–off among the farmers who considered using human urine as a fertiliser to be a bad idea. It is essential to note that none of these farmers knew anyone who uses or used urine as a fertiliser. A typical comment on this statement was that urine would make soil 'poisonous' and reduce its fertility. Here, it is assumed that the farmers are talking about foliar burning which is caused if urine is sprayed onto the leaves; high salt concentrations and drying of urine on the leaves results in reduced productivity and in extreme cases, crop die–off (Vinnerås et al. 2003). Farmer number 12 did remark, '…..urine cannot be sprayed but maybe it can be applied if it is mixed with cow dung'. A majority (92%) of the farmers stated that their current use of animal manure and/or chemical fertilisers vis–à–vis their fertiliser requirement makes urine recycling less attractive. The farmer opinions on change in the taste of crops and vegetables due to urine application were found to significantly differ by type of farming carried out ($p < 0.01$). While 63% of the organic farmers believe that the taste will change none of the inorganic farmers thought so.

Health risk from human urine is not a crucial factor discouraging the farmers who think using human urine is a bad idea (Fig. 30). Lienert et al. (2003) in a survey of 125 Swiss farmers reported that 30% of the farmers were concerned and raised doubts regarding urinary hormones and pharmaceutical residues. In the present study, none of the farmers who believed urine poses health risks expanded on, or remarked, as to why they felt so. Among the Swiss farmers environmental awareness is high; they have also been made accountable for various environmental problems (eutrophication, land degradation) in the country (Belz 2004). In contrast, ever since the adoption of the Green Revolution and the goal of modernising and industrialising the agriculture sector, Indian farmers have largely been predisposed towards chemical fertilisers and pesticides and encouraged to streamline themselves into large–scale irrigation schemes (Frankel 2015). It is estimated that 11–27% of the agricultural output in India is lost to poor soil management practices, over–farming (intensification), over–fertilisation and improper irrigation (Scherr 1999).

Bad odour has often been cited as a significant factor inhibiting the proliferation of urine recycling as well as that of urine diversion toilets (Lienert et al. 2003; Nawab et al. 2006; Mariwah and Drangert 2011). In Vellore, while farmers who do not like the idea of using urine as a fertiliser did point towards bad odour as an issue, it certainly did not rank amongst their highest concerns. Also, no significant difference was observed between the mean responses of the farmers against any of the socio–demographic variables. This is in stark contrast to a comparable case study of Ghanaian farmers who reported 'smell' to be prime factor hindering their use of 'sanitised' urine (Mariwah and Drangert 2011).

Fig. 30: Factors that encourage/discourage positive and negative attitudes towards urine recycling among the remaining 62 respondents; the ones answering that it was a good idea were asked take a stance on a number of positive statements on fertilising with human urine while the ones that did not think it was a good idea were asked to take a stance on a number of negative statements; the respondents were given the options – yes (black), no (grey) and cannot say (white)



Every societal group approaches and manages its excrement based on their codes of social conduct which varies based on their demographical, cultural and socio–economical characteristics (Tanner 1995). In South India, this responsibility has traditionally been shouldered by the lowermost sections of the society as sanitation and all activities in relation to it continue to be discriminated as 'polluting labour' (Human Rights Watch 2014). Among the farmers with negative attitude towards urine use in agriculture, 85% believe that people would mock them and/or make fun of them if they did use human urine. In this survey, this represents the second most important factor that discouraged respondents against using urine as a fertiliser. There was no caste–based difference in the mean responses of the farmers to this statement, although all of them belonged to low and middle income groups. Both the upper castes and the lower castes seem to agree that the use of urine on their farms would risk them being ridiculed although the reasons for such beliefs may differ between the castes. In India, social stratification and organisation demands that the upper castes consider sanitation and its related activities as 'repulsive' and 'polluting'. Besides, centuries of tradition have gone on to establish not only a broad congruence between caste and class (Chakravarti 2005), but also an inter–generational inheritance of occupations that people can prescribe to. Perhaps, their position in the society and in the caste hierarchy is what creates the hesitation among the upper caste farmers to consider using urine. Conversely, among the farmers belonging to the lower sections, the lingering fear of returning to their erstwhile unfavourable positions as manual scavengers and sanitation workers could be the reasons for holding negative attitudes.

The last statement on whether the farmers would 'never use urine' disclosed that, among all the farmers with negative attitude (N = 36), 31% still responded that they would certainly consider using human urine. Presumably, this consideration will most likely be shaped based on how, and by whom, their concerns surrounding urine recycling are addressed. In rural India, it is quite common for farmers to rely on the advice of people they know, they are related to and in many cases, cordial neighbour farmers. Gandhi et al. (2009) in their survey of 375 households in Karnataka observed that, even though several farmers have been approached repeatedly by experts in the past, they were more inclined to turn to a friendly neighbour for advice than to rely on confounding expert recommendations. Hence, for any misconceptions such as the 'poisonous' effect of urine on soils to be removed, it is imperative that the know–how of urine recycling, its safe application, benefits and productivity gains are demonstrated to farmers who are considering using it by farmers who are already following such practices.

3.6.7. Dry versus liquid fertilisers from sanitation systems

When confronted with the question of whether they would prefer buying and using dry fertilisers manufactured from urine, the farmer responses were predominantly positive (Fig. 31). 26% of the farmers had no opinion; disregarding the non–response, of those who took a stance (N = 51), 80% stated that they would buy a dry urine–based fertiliser in comparison to their earlier stance where only 56% responded positively (N = 62) towards the use of human urine (liquid). Accordingly, there seems to be a preference towards dry fertilisers manufactured from urine rather than using liquid urine. The inorganic farmers behaved significantly different from the rest in that, a majority of them would buy the dry fertiliser (84%).

However, among these, 68% would buy it only if the cost is cheaper or similar to their current expenditure. Similar preferences especially in terms of the form of the fertiliser (solid/liquid) were also seen in the case of Swiss Integrated Production (IP) and vegetable farmers that also purchase additional fertilisers like the inorganic farmers participating in this study (Lienert et al., 2003). Among the remaining 62 respondents, 44% of the farmers said they would buy it only if it costs lesser than what they currently pay for fertilisers, 15% stated they would buy it if its cost is similar to what they pay now while, 41% said they would buy it irrespective of the cost. When compared across various age groups, the responses differed significantly in that none of the young farmers would consider buying it (p = 0.02). Interestingly, all except one farmer who stated that they knew someone using or having used urine (question 16) indicated here that they would buy urine–based fertiliser (p = 0.03).

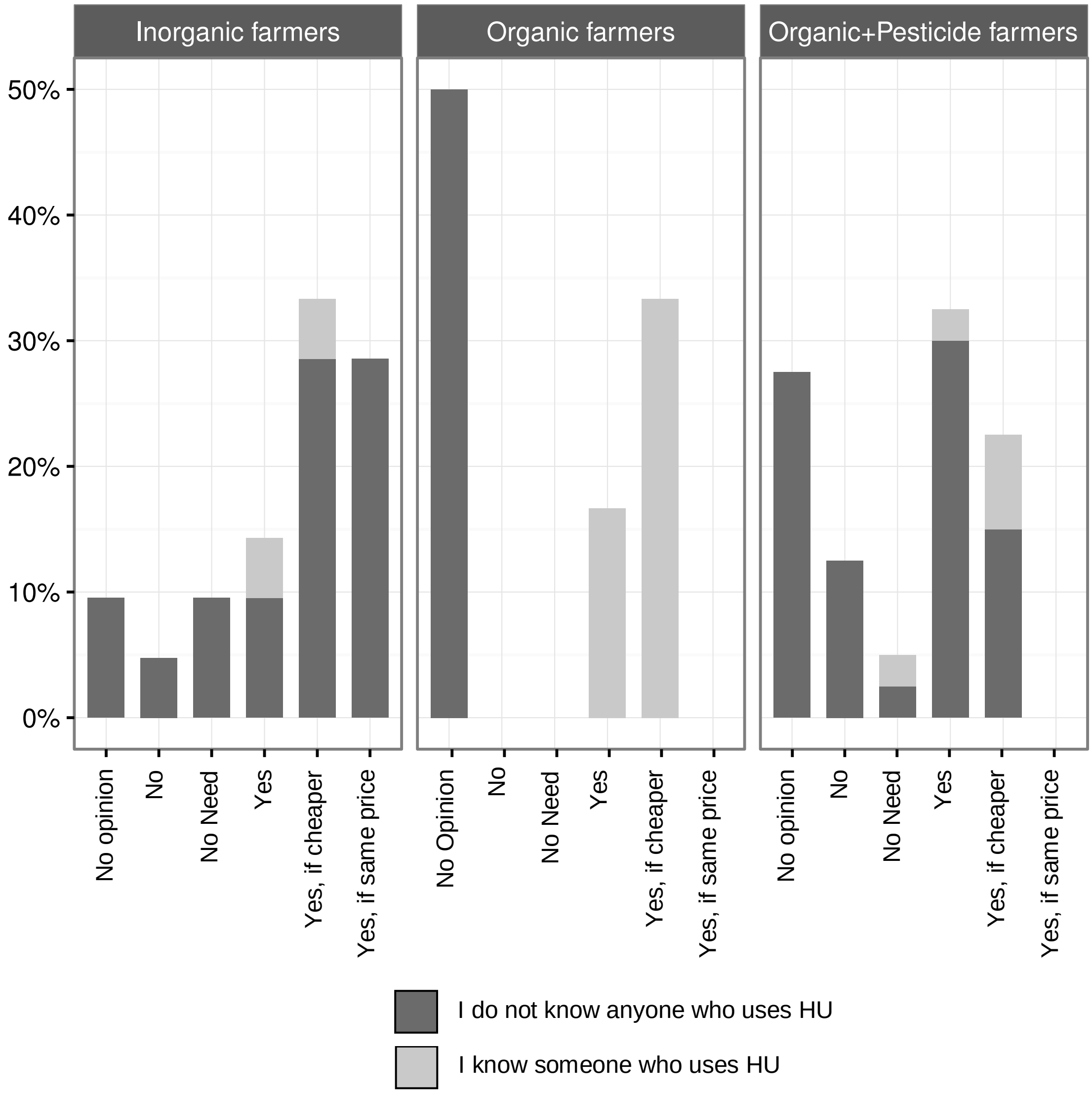


Fig. 31: Representation of respondent willingness to buy dry urine–based fertiliser, separated into type of farming (inorganic, organic and organic+pesticides) and whether (light grey) or not (dark grey) they know someone that uses or has used urine as a fertiliser

3.6.8. *Faecophobia: its existence and its extent*

Drangert (1998) noted that people's perceptions of urine differ from that of faeces. When asked to provide an opinion on human faeces, 46% of the respondents stated that it was a good (N = 23) or very good idea (N = 8) to use it as a fertiliser. Again, the young farmers were found to behave significantly different ($p < 0.1$); none of the young farmers thought using faeces as a good idea. Moreover, the 'pure organic' farmers either did not have an opinion or thought it was a bad idea ($p = 0.03$) (Fig. 32). A few respondents remarked that they were aware of the fertilising nature of faeces and that they knew people who are currently using it and/or that they knew people who used to apply faeces a few decades ago.

Winblad and Simpson–Hébert (2004) in their analysis of potential obstacles to ecological sanitation talk about modern society's fear of human faeces and refer to this as, '*faecophobia*'. The authors point towards Hinduism as a prime example to illustrate the fear of faeces which is considered 'unclean' by upper caste Hindus. In the present survey conducted on randomly selected farmers in Vellore, no caste–based difference in farmer attitudes toward use of faeces was found. Certainly, the upper caste farmers were essentially against the idea of using faeces (50%) but it is important to note that their proportion in Vellore is very low (< 10 %) to begin with. Despite the upper caste accounting for a large proportion of total landholdings in India, the other backward classes, scheduled castes and scheduled tribes far outnumber them in terms of number of cultivators and agricultural labourers (Census 2011).

According to a National Sample Survey Organisation study of 2006, the other backward class accounted for 41% of the total population in India (NSSO 2007); it is also estimated that the other backward class accounts for more than a third of all the landholdings in India (Mudgal 2006; Byres et al. 2013). In addition, it is the people belonging to the lower castes that work as agricultural labours and marginal farm–workers on upper caste owned farms (Fuller and

Narasimhan 2014). Although not tested in this survey, it would be very interesting to observe the attitudes of upper caste 'landowners' towards their agricultural labourers applying and using human wastes on their lands. Similarly, it would be equally interesting to elicit the willingness of labourers to do so. Providing this distinction could possibly result in different answers than the ones found in this study.

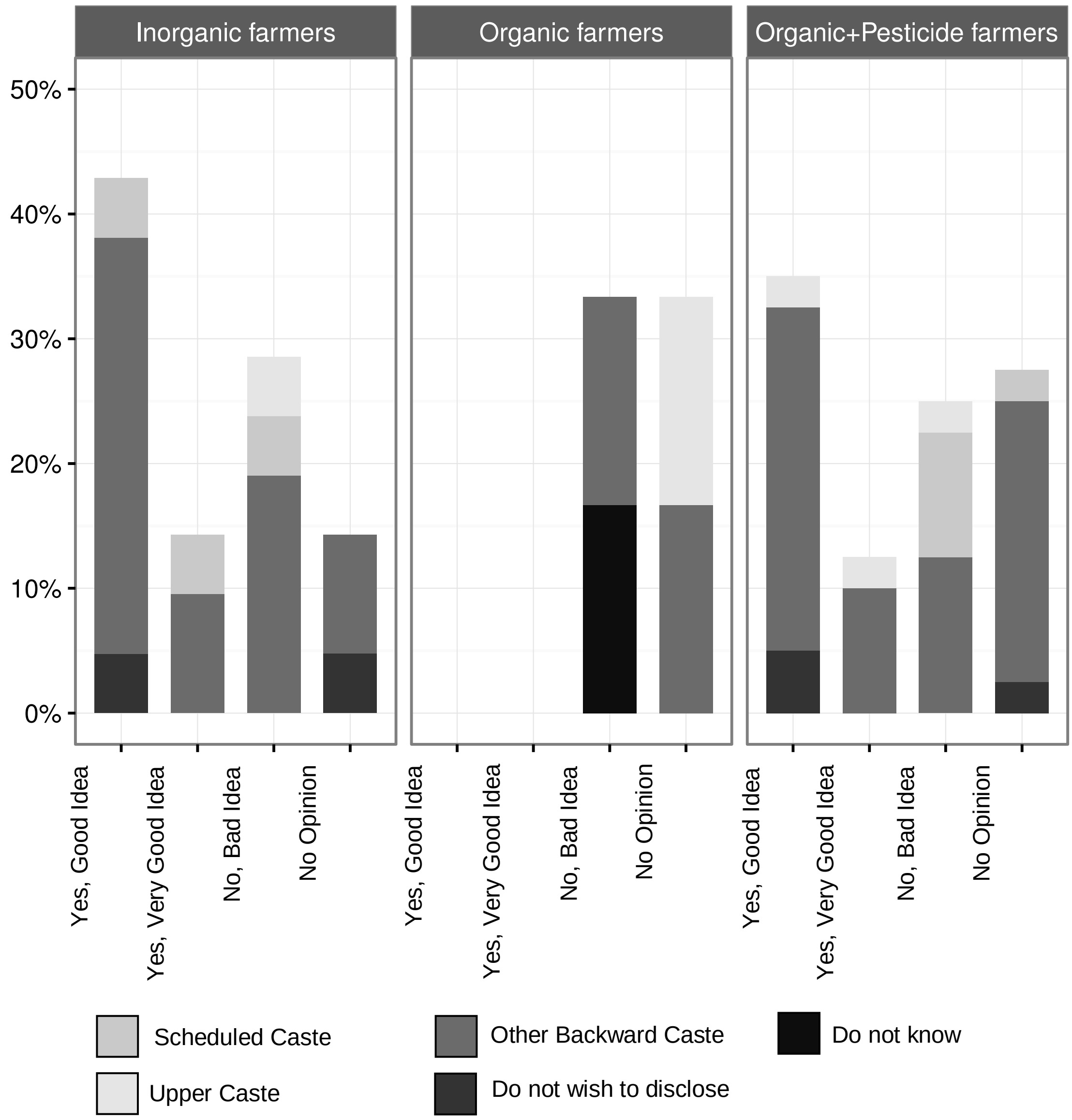


Fig. 32: Graphical representation on whether or not the respondents would consider using human faeces on their land as fertiliser, separated into the type of farming the respondents identify themselves as practicing – inorganic (left panel), organic (middle panel) or organic+pesticides (right panel) – and what caste the respondent belong to; do not know (black), do not wish to disclose (dark grey), other backward caste (medium grey), scheduled caste (light–medium grey) and upper caste (light grey)

There appears to be some degree of faecophobia in Vellore and conceivably, this is also the case in other parts of India and the world, judging from studies conducted elsewhere. However, it would be erroneous to overestimate its extent and to simply go on assuming that faecophobia exists in our societies and that people would not be open to the idea of nutrient recycling from faeces. Understanding the origins for the existence of such perceptions certainly holds key to deconstructing the reasons for faecophobia and in providing insights to dispel them.

3.6.9. Mediating the proliferation of waste recycling by 'tipping points'

Based on the analysis of farmer attitudes and perceptions in Vellore, some salient observations can be drawn. Irrespective of how the farmers answered the survey or what positions they took on various questions, there is certainly an interest in human waste recycling and reuse in agriculture. However, as seen through this survey, early dialogue, continuous interaction as well as integration of stakeholders (producers and consumers) in the conceptualisation, design and implementation of nutrient recycling programs will be imperative to ensure its continued progress and adoption. This will surely necessitate further psycho–sociological research on the subject.

Undoubtedly, the demographic, economic, cultural and traditional attributes of a society shape its approach and management of issues. However, besides the socio–demography there could be several other significant factors that might have to be taken into consideration when planning and implementing nutrient recycling programs. In the case of Vellore farmers for instance, 'trust' is a key variable that could determine the proliferation potential of human wastes recycling. Here, farmers trust and value the opinions of people they know, people they are related to, or, people whom they have been seeing and interacting with over the years; this was elicited in the present study where it was observed that none of the respondents that knew someone using human urine as a fertiliser though it was a bad idea to use it on their own crops

(Fig. 29 and Fig. 31). Considering this and acknowledging the diversity in the Indian farming sector, any further investigations should be also be carried out at a community/regional level.

It has long been assumed that, in order to adopt a new paradigm such as ecological sanitation, fundamental behavioural changes and modifications will be required across an *entire* community or society (McLeroy et al. 1988; Brown 2003; Barnes et al. 2004). However, contrary to this supposition, there lies a possibility that, current system could be replaced or at least substantially modified *if* its 'tipping points' are identified, understood, grasped and significantly influenced (Helbing 2013). Tipping points represent parameters which are critical in determining a system's properties and influencing which can result in entirely new set of system properties. For Vellore, one such tipping point appears to be – convincing a few selected farmers largely in favour of alternative modes of fertilisation to adopt urine/faecal recycling on their farms. Given the intimate and interconnected nature that appears to regulate the views on farming practices held within the Indian farming community, such influence could stimulate the creation of a positive–cascade effect across the entire rural area. I hypothesize this concept through Fig. 33. Let us consider a hypothetical community consisting of 15 farmers of which, there are 3 farmers whose influence over the entire community is considerably larger than the rest. The reasons for such influence could be because (i) they have been farming in the community for very long periods of time (say, > 15 years) and possibly know the rest of the farmers in the area, or (ii) people have known to seek their advice in the past or, (iii) that they own and operate large tracts of land and therefore, determine the net agricultural production of the community or, (iv) they have been known to adopt and implement new ways of production/fertilisation in the past (say, during the Green Revolution) which influenced others surrounding them, etc.

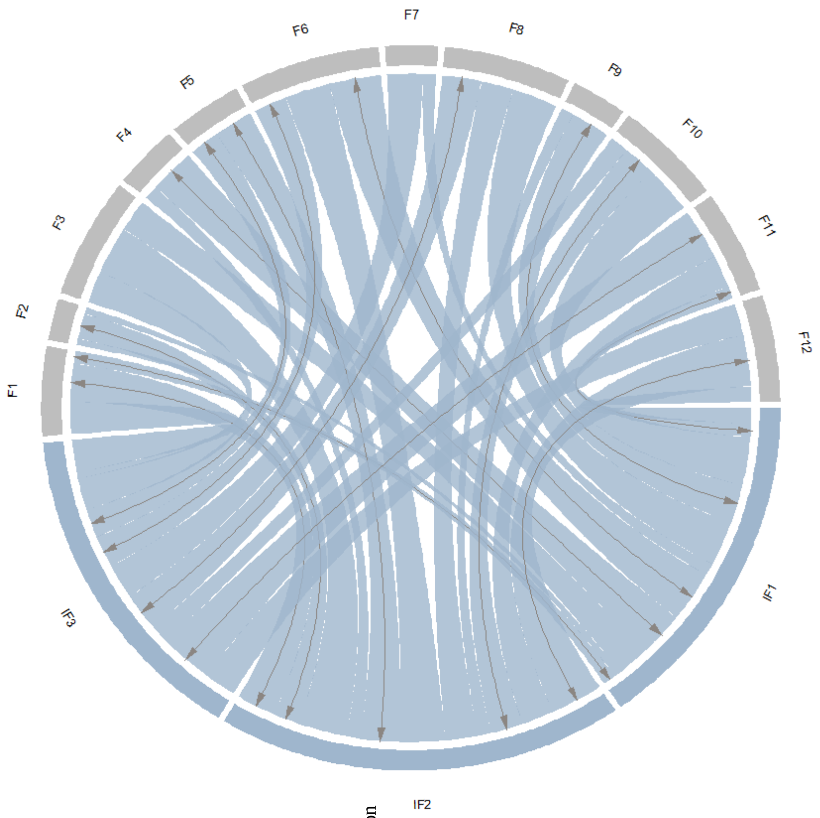
In order to provide a distinction between the farmers, I designate these 3 farmers are 'Influential Farmers' (IF) and the rest as 'Normal Farmers' (F, varying as F1 to F12).

Fig. 33 (a) illustrates the current state of affairs in the farming community. The sector area occupied by each farmer depicts the degree and extent to which he/she influences the rest. The arrows show direct interaction among various farmers (between the IFs and the Fs); an interaction where no arrow is provided signifies the presence of an indirect influence. For instance, neighbouring farmer (F12) could be influenced by the practices of IF1 even though they might not know each other or have any formal exchanges.

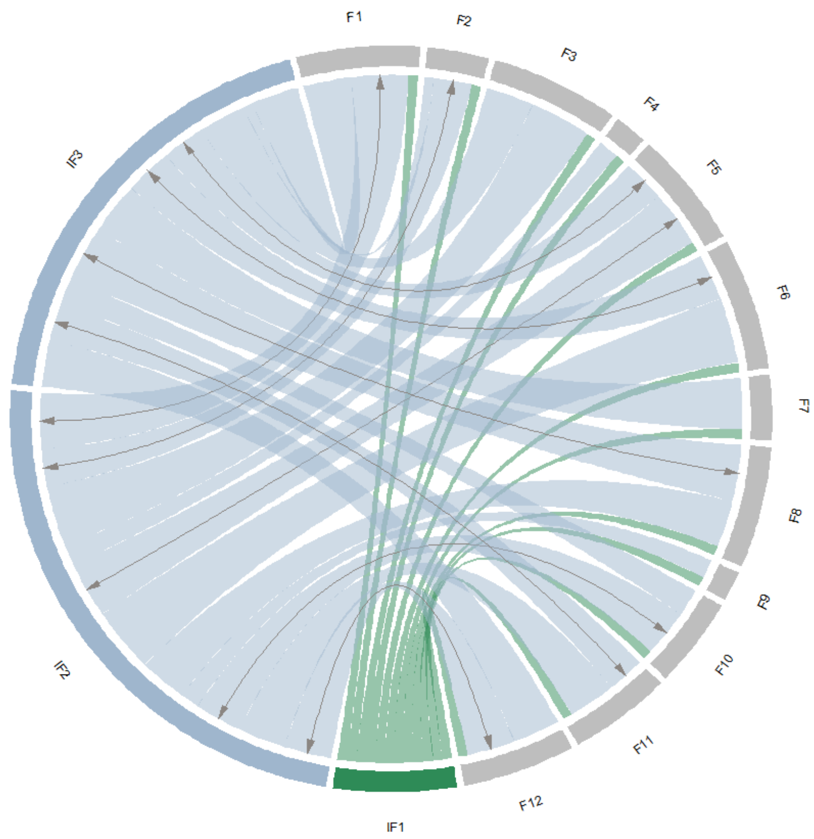
At this point let us assume that IF1 is a 'tipping point farmer'; someone who is largely in favour of urine recycling and would be willing to adopt and implement it on his/her farm. The properties of this system start changing (Fig. 33 (b)) from the moment IF1 comes to a decision on its adoption (indicated here in green). While IF2 and IF3 continue their previous interactions based on conventional modes of production with rest of the farmers, IF1 now takes the time to test the agronomic as well as economic incentives of switching over to using urine or urine based fertilisers. During this time, presumably, IF1 does interact with other farmers in his or her sphere of influence; however, it is quite likely that the extent of this interaction is low since IF1 himself/herself is testing the new system.

Significant changes to system properties occur when IF1 starts exerting influence (Fig. 33 (c)). It is assumed here that, over time, IF1 starts seeing the benefits of urine recycling. Due to this, IF1, in interactions with neighbours, relatives, friends or other farmers is able to not only describe to other farmers the reasons for using urine but also physically demonstrate its benefits in terms of productivity gains. In lieu of these interactions, some farmers (F1, F4, F12 and F10) now shift towards urine recycling while others remain unconvinced. 'Trust' in this situation is vital; only farmers that trust the opinions, judgement and practices of IF1 would be willing to try alternative fertilisation techniques. With time, the farming community attains a transitional set of system properties with many farmers now formally incorporating urine recycling into their agricultural production (Fig. 33 (d)).

Fig. 33: Hypothetical illustration of a positive cascade effect mediated via 'tipping point farmers'

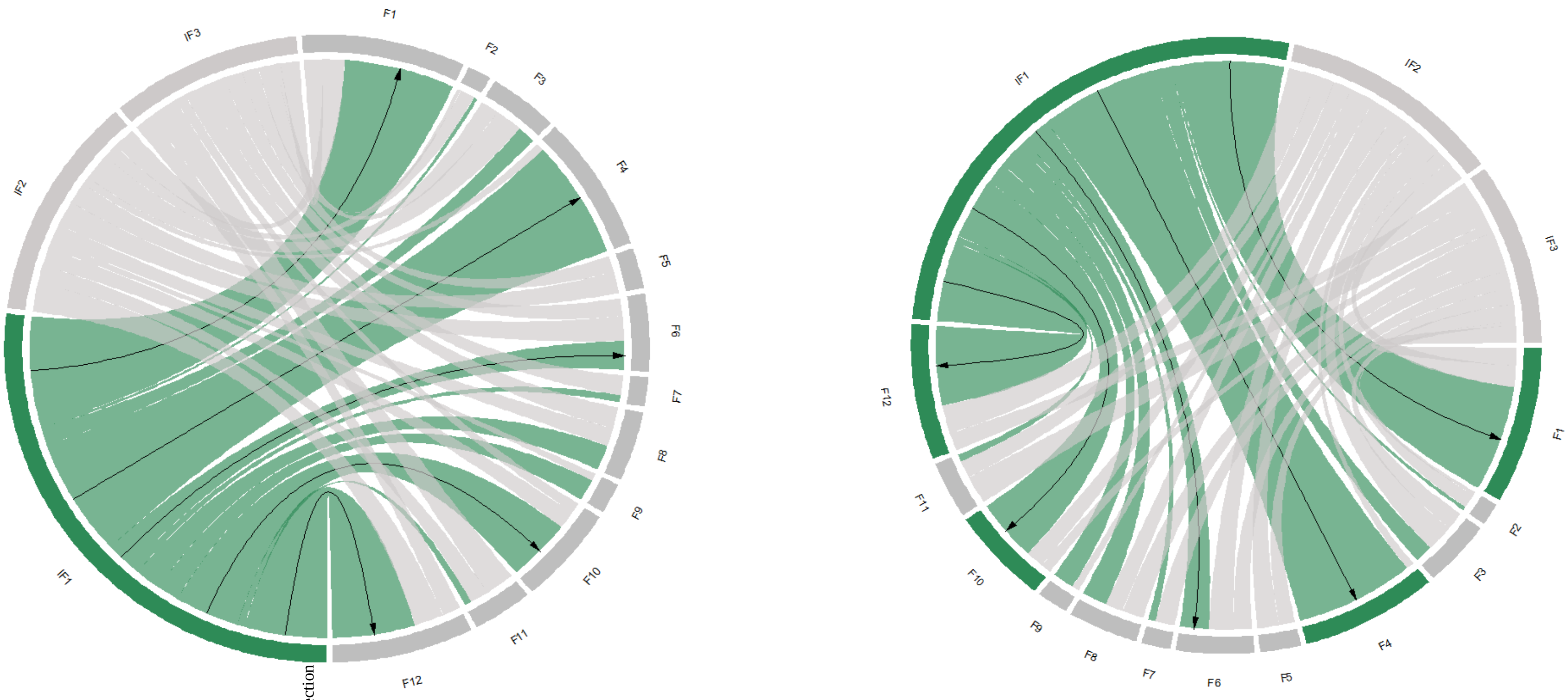


(a)



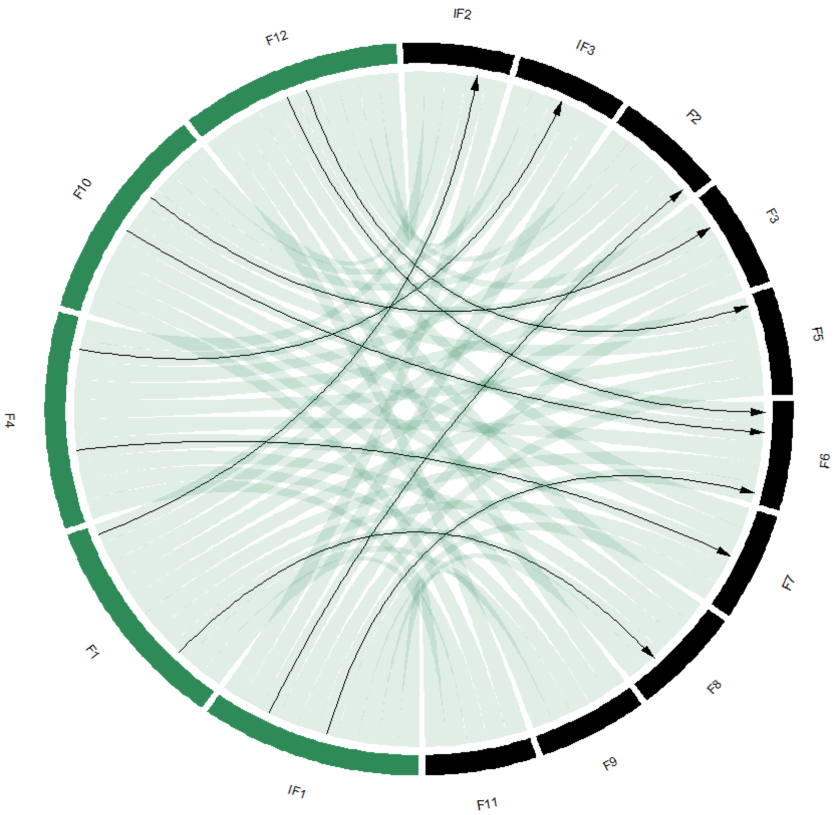
(b)

Fig. 33: Hypothetical illustration of a positive cascade effect mediated via 'tipping point farmers'



(c)

(d)



(e)

Fig. 33: Hypothetical illustration of a positive cascade effect mediated via 'tipping point farmers'

Since the system is perceived to be dynamic, it starts changing once again as seen through Fig. 33 (e) where, farmers who adopted urine recycling in the previous cycle start influencing other farmers in their sphere of interaction to realise the creation of a positive–cascade.

3.6.10. The consumer–producer disconnect

Previous studies that recorded the acceptance of No–Mix toilets among consumers of urban, semi–urban and eco–housing settlements in Switzerland, Sweden, Germany, Austria, Netherlands, Luxembourg, the US and Mexico have found that there is high acceptance of urine diversion toilets and reuse of human wastes for food production (Lienert and Larsen 2006; Lienert and Larsen 2009; Lienert 2013 Lamichhane and Babcock 2013). On the other hand, Lienert et al. (2013) and Lienert (2013) in their surveys indicate that farmers were worried about reduced sales and low consumer acceptance of urine–fertilised food. The same concerns were also voiced by farmers in Vellore where only 25% were of the opinion that consumers would be willing to buy urine–fertilised food. Even among farmers with a positive response, many stated that they would not inform their consumers about their practices.

Based on these studies it would appear that there is disconnect between the producer and the consumer. In the closed–loop sanitation cycle, the consumer represents both the source of nutrients (human wastes) as well as the potential recipient of (recycled) food while, the producer represents the potential recipient of the wastes (temporary sink) and the supplier of food.

However, despite some indications that consumers may be willing to accept new systems of sanitation and fertilisation/food production, there is reluctance among the producers to close this nutrient loop. This could be because they might be unaware of the creation or existence of such willingness among consumers or it could be because they do not believe in such positive indications. This is perhaps an unintended consequence of modern agriculture and the way our food systems have been structured. Nevertheless, for urine recycling to become a reality, it will be imperative to demonstrate to the farmer that there is willingness among their consumers to buy urine–fertilised food. Only through such integration and creation of a value chain can urine recycling become attractive enough for both, the consumers and the producers to shift away from their current practices.

4. Conclusions

Through a technological perspective, this study depicted a novel approach for promoting ecologically–sound sanitation practices. To permit a high degree of safe nutrient recycling of human wastes, the approach took advantage of source–separation in urine diversion dry toilets and integrated it sequentially with a combination of anion–exchange and alkaline dehydration processes.

Anion exchange using a strong base resin was found to be an effective pre–treatment step for alkalinisation and nutrient preservation in human urine. Initial studies indicated that at least 75% of the urine must interact and pass through the resin to achieve the necessary elevation of pH (≥ 11); this followed by storage of urine below a temperature of 37°C stabilised it for a period of at least two weeks.

Operating the sieve–based drying setup at 50°C, 1 $L.min^{-1}$ suction flow rate and ash loading of 100 g resulted in very high drying rates (11.93 ± 1 $L.day^{-1}.m^{-2}$). This suggested that, less than 10 kg of wood ash would be required to process the monthly urine production of a household (4 members) in just 4.15 days. Furthermore, on account of volume minimisation that occurs in alkaline dehydration, the use of a urine drying unit would make each person accountable for just 21–64 kg of nutrient rich products (urine + drying media) instead of 500 kg of waste (urine) every year. In all the drying protocols, > 70% N retention and complete recovery of P and K in the drying media was accomplished.

A mathematical basis was established through empirical modelling which pointed out that diffusion–controlled mass transfer and the Page equation best described the urine drying over wood ash. In addition, optimisation of the drying rate within an investigated range of input variables using Response Surface Methodology was also demonstrated.

Through a sociological perspective, the survey of farmers in Vellore (India) provided insights that add to the current discourse in environmental psychology which seeks to understand the factors that encourage or discourage the adoption of environment–friendly technologies. When confronted with the question whether they thought human wastes could be used as a fertiliser, of the farmers who took a stance, 59% answered positively towards the use of urine while 46% felt it would be a good idea to use human faeces.

Interestingly, farmers in Vellore appeared to display what I call, a *not–in–my–circle* syndrome as they would rather see their neighbours use human urine than their friends, family and colleagues. Improved soil quality and potential cost savings from the reduced use of chemical fertilisers were found to be the primary factors that motivated farmers to respond positively towards the possibility of using human urine. Moreover, 78% of the respondents that indicated a positive attitude considered urine to be ‘safe’ fertiliser despite little or no information over its sanitisation or concentration of micro–pollutants and pharmaceuticals.

On the other hand, the reasons that discouraged urine recycling among the farmers with a negative attitude included crop die–off, the risk of being ridiculed and uncertainty over their consumer’s market–place behaviour. The survey also indicated that, for farmers to adopt human urine as a fertiliser either they must know someone who uses (or used) it and/or must be convinced of its crop productivity potential; any consideration of human waste recycling in Vellore will most likely be shaped by how, and by whom, the concerns of the farmers are addressed. To this effect, this study also provided a conceptual pathway that can help mediate the proliferation and adoption of nutrient recycling practices in agriculture.

In conclusion, this study, by combining both the technological and sociological perspectives, described how, the toilet (sanitation), a simple innovation that forms part of everyday life holds tremendous potential to bridge the wider technology–society gap and promote environmentally conscious behaviour among users.

5. Further research

Perhaps no socio–technical innovation or technology today is truly sustainable. However, ecological sanitation with its rationale for recycling nutrients in an effort to emulate natural biogeochemical cycles certainly holds promise of *strong* sustainability. In line with this thinking, this study advocated the decentralisation of sanitation systems through the integration of anion–exchange and alkaline dehydration process in a urine diversion dry toilet. Some suggestions for further research have been provided below;

a. While alkalinisation and a threshold pH of ≥ 10.5 should be sufficient in disinfecting the human urine over a drying media, further feasibility studies over model virus and parasites are necessary to validate this.

b. Reapplication of the dried urine + ash mixture in soils through pot and field trials will be necessary to evaluate its fertiliser value and plant availability of nutrients as against synthetic fertilisers.

c. From a techno–economic feasibility point of view, tools such as Life Cycle Analysis could provide the insights into the potential competitiveness of the proposed system against conventional fertiliser production and consumption.

d. The 'tipping point' farmer approach put forward in this study could help mediate and augment the proliferation of nutrient recycling programs. It would be interesting to investigate how these farmers could be identified in a community and positively influenced to realize a positive cascade effect in adoption.

e. Since socio–demography, culture and geography influences people's perception of (ecological) sanitation, a study co–investigating the consumer and producer perspectives and attitudes towards urine drying and nutrient recycling within a community should be investigated.

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Appendix

Appendix AX1: pH of various urine fractions due to ion exchange with a fixed resin loading of 20% v/v

% Diversion	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6	Sample 7	Sample 8	Sample 9	Sample 10
0	6.38	7.06	6.81	7.16	6.78	6.80	6.71	6.71	6.61	7.15
20	7.05	8.35	7.25	8.27	7.90	8.52	8.53	7.15	6.85	7.59
40	7.32	9.26	8.63	9.68	9.95	9.81	9.62	8.61	7.42	9.38
60	7.26	9.67	9.41	10.20	11.28	10.47	10.46	9.28	8.29	10.12
80	7.16	9.86	9.65	10.60	11.64	10.65	11.26	10.02	9.83	10.64
100	7.06	9.88	9.84	10.68	12.02	10.67	11.51	10.59	10.44	10.55

% Diversion	Sample 11	Sample 12	Sample 13	Sample 14	Sample 15	Sample 16	Sample 17	Sample 18	Sample 19	Sample 20
0	7.15	6.91	6.75	7.05	7.08	6.80	7.11	6.62	7.37	7.03
20	8.27	7.22	7.48	7.78	7.32	8.22	8.92	8.42	8.75	8.50
40	9.02	7.69	8.56	9.22	9.25	9.41	9.84	9.54	9.52	9.20
60	9.39	8.45	9.87	9.81	10.18	10.38	11.04	10.22	10.13	9.87
80	9.40	8.84	10.55	10.10	10.77	11.08	11.68	11.05	10.48	10.11
100	9.45	9.55	11.11	10.49	10.91	11.23	12.04	11.58	10.36	10.15

% Diversion	Sample 21	Sample 22	Sample 23	Sample 24	Sample 25	Sample 26	Sample 27	Sample 28	Sample 29	Sample 30
0	7.14	5.77	6.79	6.90	5.56	5.55	5.85	6.81	5.83	7.16
20	8.65	7.31	9.74	9.89	6.59	6.84	6.75	8.15	6.31	8.36
40	9.45	8.61	10.13	10.44	8.27	8.37	8.25	9.26	6.65	9.34
60	10.09	9.69	11.29	11.30	9.82	9.58	9.58	10.14	7.14	9.88
80	10.43	10.39	11.73	11.71	9.96	10.17	9.94	11.09	7.95	10.46
100	10.31	10.80	11.88	11.93	11.09	10.48	10.55	11.49	10.08	11.63

% Diversion	Sample 31	Sample 32	Sample 33	Sample 34	Sample 35	Sample 36	Sample 37	Sample 38	Sample 39	Sample 40
0	6.60	6.78	5.79	5.82	6.28	6.84	6.88	6.33	5.98	5.96
20	7.49	7.42	8.44	8.41	8.17	8.48	7.97	7.81	7.52	7.53
40	8.67	8.16	9.26	9.26	9.74	9.72	9.43	9.19	8.87	8.82
60	9.64	8.09	10.51	9.85	10.41	10.18	9.84	9.94	9.65	9.68
80	10.23	8.23	11.37	10.21	11.42	10.97	10.59	10.43	10.23	10.21
100	11.86	8.48	11.98	10.84	12.14	11.68	11.18	10.81	10.22	10.24

% Diversion	Sample 41	Sample 42	Sample 43	Sample 44	Sample 45	Sample 46	Sample 47	Sample 48	Sample 49	Sample 50
0	6.42	6.25	6.37	6.49	6.86	6.45	6.55	6.58	6.99	6.71
20	8.43	7.28	8.07	8.02	8.18	8.15	8.18	8.98	9.02	9.11
40	9.38	8.66	9.16	9.21	9.31	9.05	9.09	9.56	10.59	10.05
60	10.43	9.26	10.11	10.08	10.07	9.98	9.96	10.41	11.22	10.59
80	10.84	9.92	10.62	10.58	10.49	10.22	10.64	11.55	1.55	11.36
100	11.21	10.85	11.11	10.95	10.88	10.76	11.09	12.33	11.98	11.59

Appendix AX2: Statistical analysis for questions 15–17.2 of the farmer surveys: Part 1

Demographic Variable	Question 15				Question 16				Question 17.1				Question 17.2			
	N[a]	Y[b]	μ[c]	*p*–value	N	Y	μ	*p*–value	N	Y	μ	*p*–value	N	Y	μ	*p*–value
Gender																
Male	34	46	1.58	0.0434*	65	15	1.19	0.6680	33	47	1.59	1.0050	72	8	1.10	0.3557
Female	13	5	1.28		16	2	1.11		7	11	1.61		18	0	1.00	
Age																
< 30	3	4	1.57	0.2660	7	0	1.00	0.5990	3	4	1.57		6	1	1.14	0.9440
30–45	14	13	1.48	1.3410	21	6	1.22	0.6280	10	17	1.63	0.9070	25	2	1.07	0.1270
45–60	15	25	1.63		33	7	1.18		18	22	1.55	0.1840	37	3	1.08	
> 60	15	9	1.38		20	4	1.17		9	15	1.63		22	2	1.08	
Family Size																
≤ 3	10	4	1.29	0.00711**	14	0	1.00	0.00582**	7	7	1.50	0.5960	14	0	1.00	0.1330
3–4	8	24	1.75	4.2730	29	3	1.09	4.4360	12	20	1.63	0.6320	29	3	1.09	1.9150
4–6	23	16	1.41		31	8	1.21		14	25	1.64		37	2	1.05	
> 6	6	7	1.54		7	6	1.46		7	6	1.46		10	3	1.23	
Caste																
Scheduled Caste (SC)	4	7	1.64	0.2520	11	0	1.00	0.1200	3	8	1.73	0.0811†	11	0	1.00	0.5100
Scheduled Tribe (ST)	0	4	2.00	1.3460	4	0	1.00	1.8030	0	4	2.00	2.0340	4	0	1.00	0.8620
Other Backward Caste (OBC)	34	33	1.49		53	14	1.21		33	34	1.51		61	6	1.09	
Upper Caste (UC)	6	3	1.33		8	1	1.11		2	7	1.78		7	2	1.22	
Do not know	0	1	2.00		0	1	2.00		1	0	1.00		1	0	1.00	
Do not wish to disclose	3	3	1.50		5	1	1.17		1	5	1.83		6	0	1.00	

[a] No; [b] Yes; [c] Mean response; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$; † $p < 0.1$; values highlighted in green are very close to $p < 0.1$

Appendix AX2: Statistical analysis for questions 15–17.2 of the farmer surveys: Part 2

Demographic Variable	Question 15				Question 16				Question 17.1				Question 17.2			
	N[a]	Y[b]	μ[c]	*p*–value	N	Y	μ	*p*–value	N	Y	μ	*p*–value	N	Y	μ	*p*–value
Annual Income																
≤ 45000 ₹	13	26	1.67	0.1110	32	7	1.18	0.8750	15	24	1.62	0.7950	38	1	1.03	0.3480
45,000 – 100,000 ₹	16	14	1.47	2.0550	25	5	1.17	0.2300	13	17	1.57	0.3420	26	4	1.13	1.1130
> 100,000 ₹	2	1	1.33		3	0	1.00		2	1	1.33		3	0	1.00	
Do not wish to disclose	16	10	1.38		21	5	1.19		10	16	1.62		23	3	1.12	
Farm Size																
≤ 1	21	26	1.55	0.00711**	37	10	1.21	0.7870	17	30	1.64	0.2770	43	4	1.09	0.7160
1–2	8	14	1.64	4.2730	19	3	1.14	0.3530	8	14	1.64	1.3060	20	2	1.09	0.4520
2–4	9	7	1.44		14	2	1.13		7	9	1.56		14	2	1.13	
> 4	8	4	1.33		10	2	1.17		8	4	1.33		12	0	1.00	
Farm time																
≤ 2	1	5	1.83	0.4140	6	0	1.00	0.1150	3	3	1.50	0.7120	6	0	1.00	0.4820
2–4	6	7	1.54	0.9620	13	0	1.00	2.0270	6	7	1.54	0.4590	13	0	1.00	0.8280
4–6	2	1	1.33		3	0	1.00		2	1	1.33		3	0	1.00	
> 6	38	38	1.50		59	17	1.22		29	47	1.62		68	8	1.11	
Farm type																
Organic	5	8	1.62	0.6650	10	3	1.23	0.3150	4	9	1.69	0.0418*	13	0	1.00	0.4850
Inorganic	14	12	1.46	0.4090	24	2	1.08	1.1700	16	10	1.38	3.2820	24	2	1.08	0.7280
Organic+Pesticides	28	31	1.53		47	12	1.20		20	39	1.66		53	6	1.10	

Appendix AX3: Statistical analysis for questions 18–20 of the farmer surveys: Part 1

Demographic Variable	Question 18					Question 19					Question 20					
	CS[a]	N[b]	Y[c]	μ[d]	*p*–value	CS	N	Y	μ	*p*–value	B	G	NA	VG	μ	*p*–value
Gender																
Male	28	32	20	1.25	0.8423	32	23	25	1.31	0.0945	24	30	18	8	1.48	0.1839
Female	5	8	5	1.28		4	4	10	1.56		3	9	4	2	1.61	
Age																
< 30	1	4	2	1.29	0.7340	1	3	3	1.43	0.5990	4	2	1	0	1.29	0.3600
30–45	9	8	10	1.37		8	7	12	1.44		5	9	11	2	1.41	
45–60	15	17	8	1.20		16	12	12	1.30		10	18	8	4	1.55	
> 60	8	11	5	1.21		11	5	8	1.33		8	10	2	4	1.58	
Family Size																
≤ 3	4	6	4	1.29	0.5860	4	5	5	1.36	0.6960	3	5	5	1	1.43	0.8740
3–4	13	13	6	1.19		8	14	10	1.31		9	14	8	1	1.47	
4–6	12	17	10	1.26		18	6	15	1.38		10	15	8	6	1.54	
> 6	4	4	5	1.38		6	2	5	1.38		5	5	1	2	1.54	
Caste																
Scheduled Caste (SC)	2	8	1	1.09	0.4980	3	3	5	1.45	0.4030	7	2	0	2	1.36	0.2100
Scheduled Tribe (ST)	1	3	0	1.00		4	0	0	1.00		1	2	0	1	1.75	
Other Backward Caste (OBC)	24	23	20	1.30		25	17	25	1.37		14	31	16	6	1.55	
Upper Caste (UC)	3	3	3	1.33		2	3	4	1.44		3	2	3	1	1.33	
Do not know	1	0	0	1.00		1	0	0	1.00		0	1	0	0	2.00	
Do not wish to disclose	2	3	1	1.17		1	4	1	1.17		2	1	3	0	1.17	

[a] Cannot say; [b] No; [c] Yes; [d] Mean response; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$; † $p < 0.1$; values highlighted in green are very close to $p < 0.1$

Appendix AX3: Statistical analysis for questions 18–20 of the farmer surveys: Part 2

Demographic Variable	Question 18					Question 19					Question 20					
	CS	N	Y	μ	*p*–value	CS	N	Y	μ	*p*–value	B	G	NA	VG	μ	*p*–value
Annual Income																
≤ 45000 ₹	14	16	9	1.23	0.3090	15	8	16	1.41	0.1310	9	19	6	5	1.62	0.3210
45,000 – 100,000 ₹	11	13	6	1.20		13	10	7	1.23		6	9	11	4	1.43	
> 100,000 ₹	1	0	2	1.67		0	1	2	1.67		1	1	1	0	1.33	
Do not wish to disclose	7	11	8	1.31		8	8	10	1.38		11	10	4	1	1.42	
Farm Size																
≤ 1	14	21	12	1.26	0.2330	22	12	13	1.28	0.2980	14	22	5	6	1.60	0.3850
1–2	12	5	5	1.23		8	6	8	1.36		6	1	6	0	1.08	
2–4	3	11	2	1.13		3	7	6	1.38		4	3	6	3	1.38	
> 4	4	2	6	1.50		3	1	8	1.67		3	4	4	1	1.42	
Farm time																
≤ 2	2	3	1	1.17	0.3650	3	2	1	1.17	0.4250	1	3	1	1	1.67	0.1360
2–4	4	5	4	1.31		7	2	4	1.31		2	3	7	1	1.31	
4–6	1	0	2	1.67		1	0	2	1.67		0	3	0	0	2.00	
> 6	26	32	18	1.24		25	23	28	1.37		24	30	14	8	1.50	
Farm type																
Organic	4	9	0	1.00	0.0338*	4	5	4	1.31	0.0933	1	7	4	1	1.62	0.3510
Inorganic	5	11	10	1.38		7	6	13	1.50		7	13	4	2	1.58	
Organic+Pesticides	24	20	15	1.25		25	16	18	1.31		19	19	14	7	1.44	

Appendix AX4: Statistical analysis for questions 20.1.1–20.1.4 of the farmer surveys: Part 1																
Demographic Variable	**Question 20.1.1**				**Question 20.1.2**				**Question 20.1.3**				**Question 20.1.4**			
	N[a]	**Y[b]**	**μ[c]**	***p*–value**	**N**	**Y**	**μ**	***p*–value**	**N**	**Y**	**μ**	***p*–value**	**N**	**Y**	**μ**	***p*–value**
Gender																
Male	6	24	1.80	0. 2420	14	16	1.53	0.8850	7	23	1.77	0.7290	7	23	1.77	0.6180
Female	0	6	2.00		3	3	1.50		1	5	1.83		2	4	1.67	
Age																
< 30	0	2	2.00	0.6030	1	1	1.50	0.3760	1	1	1.50	0.6170	2	0	1.00	0.0171*
30–45	1	9	1.90		5	5	1.50		3	7	1.70		2	8	1.80	
45–60	4	11	1.73		9	6	1.40		3	12	1.80		5	10	1.67	
> 60	1	8	1.89		2	7	1.78		1	8	1.89		0	9	2.00	
Family Size																
≤ 3	0	4	2.00	0.6490	4	0	1.00	0.0195*	2	2	1.50	0.4670	1	3	1.75	0.390
3–4	3	8	1.73		7	4	1.36		3	8	1.73	0.8690	4	7	1.64	
4–6	2	12	1.86		5	9	1.64		2	12	1.86		4	10	1.71	
> 6	1	6	1.86		1	6	1.86		1	6	1.86		0	7	2.00	
Caste																
Scheduled Caste (SC)	0	2	2.00	0.8120	1	1	1.50	0.6730	0	2	2.00	0.3570	0	2	2.00	0.4210
Scheduled Tribe (ST)	0	0	NA		0	0	NA		0	0	NA	1.1380	0	0	NA	
Other Backward Caste (OBC)	6	23	1.79		13	16	1.55		6	23	1.79		7	22	1.76	
Upper Caste (UC)	0	3	2.00		2	1	1.33		2	1	1.33		2	1	1.33	
Do not know	0	1	2.00		1	0	1.00		0	1	2.00		0	1	2.00	
Do not wish to disclose	0	1	2.00		0	1	2.00		0	1	2.00		0	1	2.00	

[a] No; [b] Yes; [c] Mean response; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$; † $p < 0.1$; values highlighted in green are very close to $p < 0.1$

Appendix AX4: Statistical analysis for questions 20.1.1–20.1.4 of the farmer surveys: Part 2																
Demographic Variable	**Question 20.1.1**				**Question 20.1.2**				**Question 20.1.3**				**Question 20.1.4**			
	N	**Y**	**μ**	***p*–value**	**N**	**Y**	**μ**	***p*–value**	**N**	**Y**	**μ**	***p*–value**	**N**	**Y**	**μ**	***p*–value**
Annual Income																
≤ 45000 ₹	5	11	1.69	0.1870	9	7	1.44	0.6580	4	12	1.75	0.2910	3	13	1.81	0.7260
45,000 – 100,000 ₹	0	11	2.00		5	6	1.55		4	7	1.64		4	7	1.64	
> 100,000 ₹	0	1	2.00		0	1	2.00		0	1	2.00		0	1	2.00	
Do not wish to disclose	1	7	1.88		3	5	1.63		0	8	2.00		2	6	1.75	
Farm Size																
≤ 1	1	15	1.94	0.5230	6	10	1.63	0.4380	1	15	1.94	0.0303*	2	14	1.88	0.0928†
1–2	2	6	1.75		3	5	1.63		1	7	1.88		1	7	1.88	
2–4	1	4	1.80		3	2	1.40		3	2	1.40		2	3	1.60	
> 4	2	5	1.71		5	2	1.29		3	4	1.57		4	3	1.43	
Farm time																
≤ 2	0	0	NA	0.7580	0	0	NA	0.5130	0	0	NA	0.3140	0	0	NA	0.7200
2–4	1	3	1.75		3	1	1.25		2	2	1.50		1	3	1.75	
4–6	0	2	2.00		1	1	1.50		0	2	2.00		0	2	2.00	
> 6	5	25	1.83		13	17	1.57		6	24	1.80		8	22	1.73	
Farm type																
Organic	1	4	1.80	0.5840	4	1	1.20	0.1040	3	2	1.40	0.0145*	2	3	1.60	0.0114*
Inorganic	3	9	1.75		7	5	1.42		4	8	1.67		6	6	1.50	
Organic+Pesticides	2	17	1.89		6	13	1.68		1	18	1.95		1	18	1.95	

Appendix AX5: Statistical analysis for questions 20.2.1–20.1.7 of the farmer surveys								
Variable	**Statistic**	**20.2.1**	**20.2.2**	**20.2.3**	**20.2.4**	**20.2.5**	**20.2.6**	**20.2.7**
Gender	***p–value***	0.502	0.873	0.171	0.874	0.556	0.374	0.796
Age	***p–value***	0.208	0.915	0.359	0.144	0.136	0.914	0.437
	F–value	1.644	0.171	1.128	1.997	2.054	0.172	0.943
Family Size	***p–value***	0.056†	0.0676	0.00078***	0.831	0.194	0.00159**	0.691
	F–value	2.933	2.741	8.139	0.292	1.712	7.145	0.493
Caste	***p–value***	0.558	0.0485*	0.198	0.818	0.561	0.505	0.471
	F–value	0.708	3.081	1.692	0.309	0.701	0.805	0.872
Annual Income	***p–value***	0.431	0.093†	0.278	0.592	0.465	0.0365*	0.215
	F–value	0.955	2.422	1.37	0.649	0.884	3.377	1.613
Farm Size	***p–value***	0.662	0.93	0.471	0.701	0.483	0.928	0.205
	F–value	0.537	0.148	0.872	0.477	0.847	0.15	1.659
Farm time	***p–value***	0.323	0.201	0.794	0.903	0.352	0.00458**	0.835
	F–value	1.189	1.724	0.233	0.102	1.095	6.868	0.182
Farm type	***p–value***	0.283	0.00562**	0.739	0.22	0.539	0.512	0.181
	F–value	1.334	6.546	0.306	1.62	0.635	0.689	1.844

[a] No; [b] Yes; [c] Mean response; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$; † $p < 0.1$; values highlighted in green are very close to $p < 0.1$

Appendix AX6: Statistical analysis for questions 21 and 22 of the farmer surveys: Part 1

Demographic Variable	Question 21[a]								Question 22[a]					
	NA	NB	NN	YB	YBCC	YBCS	μ	*p*–value	B	G	NA	VG	μ	*p*–value
Gender														
Male	12	5	4	15	15	3	1.61	0.865	18	20	11	5	1.43	0.923
Female	4	1	0	2	3	3	1.62		2	3	5	3	1.38	
Age														
< 30	2	3	0	0	0	1	1.17	0.0204*	4	0	2	0	1.67	0.0921†
30–45	5	2	0	4	8	1	1.65		5	7	5	3	1.40	
45–60	5	1	1	9	8	3	1.74		8	11	5	3	1.41	
> 60	4	0	3	4	2	1	1.50		3	5	4	2	1.36	
Family Size														
≤ 3	6	0	1	1	2	0	1.30	0.0597†	4	0	4	2	1.60	0.1370
3–4	6	4	0	6	5	3	1.58		8	9	6	1	1.38	
4–6	3	2	2	8	6	3	1.71		6	11	4	3	1.38	
> 6	1	0	1	2	5	0	1.78		2	3	2	2	1.44	
Caste														
Scheduled Caste (SC)	0	5	0	0	2	1	1.38	0.1050	5	1	1	1	1.75	0.3500
Scheduled Tribe (ST)	0	0	0	0	0	0	NA		0	0	0	0	NA	
Other Backward Caste (OBC)	10	1	3	16	11	3	1.68		10	18	12	6	1.35	
Upper Caste (UC)	4	0	1	0	2	0	1.29		4	1	1	1	1.71	
Do not know	0	0	0	1	0	0	2.00		1	0	0	0	2.00	
Do not wish to disclose	2	0	0	0	3	0	1.60		0	3	2	0	1.00	

[a] Refer to Appendix AX 7 for explanation of responses; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$; † $p < 0.1$; values highlighted in green ~ $p < 0.1$

Appendix AX6: Statistical analysis for questions 21 and 22 of the farmer surveys: Part 2														
Demographic Variable	**Question 21**								**Question 22**					
	NA	**NB**	**NN**	**YB**	**YBCC**	**YBCS**	**μ**	***p*–value**	**B**	**G**	**NA**	**VG**	**μ**	***p*–value**
Annual Income														
≤ 45000 ₹	4	4	2	8	7	0	1.60	0.2630	9	7	6	3	1.48	0.0971†
45,000 – 100,000 ₹	9	0	0	5	4	1	1.53		6	5	7	1	1.37	
> 100,000 ₹	1	0	1	1	0	0	1.33		1	2	0	0	1.33	
Do not wish to disclose	2	2	1	3	7	5	1.75		4	9	3	4	1.40	
Farm Size														
≤ 1	6	1	2	9	8	3	1.69	0.1250	5	12	8	4	1.31	0.2930
1–2	3	2	1	5	4	0	1.60		5	6	3	1	1.40	
2–4	4	2	1	1	3	0	1.36		6	3	2	0	1.55	
> 4	3	1	0	2	3	3	1.67		4	2	3	3	2.75	
Farm time														
≤ 2	2	0	0	0	0	0	1.00	0.1520	0	0	1	1	1.50	0.9070
2–4	5	0	0	1	2	1	1.44		2	3	4	0	1.29	
4–6	0	0	0	1	1	0	2.00		0	1	1	0	1.00	
> 6	9	6	4	15	15	5	1.65		18	19	10	7	2.39	
Farm type														
Organic	3	0	0	1	2	0	1.50	0.1530	4	0	2	0	1.67	0.0291*
Inorganic	2	1	2	3	7	6	1.76		6	9	3	3	1.43	
Organic + Pesticides	11	5	2	13	9	0	1.55		10	14	11	5	1.38	

Appendix AX7: Questionnaire for Farmer Surveys

Disclaimer and Privacy Policy: This survey is meant strictly for the purpose of academic research and all personal information disclosed herein shall not be shared with any third parties in accordance to Indian laws on data protection.
Approximate time required to fill out the Questionnaire: *30–40 minutes*

Name of Respondent/Farmer: ____

Farmer Number: ______

Location of Farm: ____

Section I

1. Gender (What is your gender?)

Male ☐
Female ☐

2. Age (What is your age?)

< 30 ☐
30–45 ☐
45–60 ☐
> 60 ☐

3. Size of Family (How many people live on your farm?)

≤ 3 ☐
3–4 ☐
4–6 ☐
> 6 ☐

4. Religion (What religion or religious beliefs do you prescribe to?)

Hindu ☐
Muslim ☐
Christian ☐
No Religion ☐
I do not wish to disclose ☐
Others ________________

5. Caste (What is your caste?)

Scheduled Tribe (ST) ☐
Scheduled Caste (SC) ☐
Other Backward Caste (OBC) ☐
Upper Caste ☐
I do not know ☐
I do not wish to disclose ☐

6. Period of Time on the Farm (For how long have you been farming?)

≤ 2 yrs ☐
2–10 yrs ☐
4–6 yrs ☐
> 6 yrs ☐

7. Annual Income (How much do you earn each year from farming or farm related activities?)

≤ 45,000 ₹ ☐
45,000 to 1,00,000 ₹ ☐
> 1,00,000 ₹ ☐
I do not wish to disclose ☐

Section II

8. Farm Size (How much land is there on your property that you use for farming or farm activities); Answer in _hectares_

≤ 1 ha ☐
1–2 ha ☐
2–4 ha ☐
> 4 ha ☐

9. Type of Farming (How do you grow your crops?; Frequency)

Please Note Type of Crop/Vegetable/Plantation grown on the Farm

Single Crop ☐ ______________________________
Two Crop ☐ ______________________________
Multiple Crops ☐ ______________________________
Multiple Crops (*with* Crop Rotation) ☐ ______________________________

10. Type of Farming (How do you grow your crops?; Fertilisers, Pesticides, etc.)

Organic (I don't use chemicals) ☐
Inorganic (I use chemical fertilisers and pesticides) ☐
Organic + Use some chemicals (say, pesticides) ☐

11. Current use of Chemical Fertilisers (Farmer's perception of Fertiliser he/she requires on farm)

Small requirement ☐
Small to Medium requirement ☐
Medium to Large requirement ☐

12. In what form do you use your fertiliser?

Liquid Fertiliser ☐
Solid Fertiliser (Grains) ☐
Others ____________________

13. Livestock/Husbandry Data (Insert <u>Number</u> for Each)

Cattle ☐
Cows ☐
Goats ☐
Chicken (Poultry) ☐
Others ☐
____

Section III

14. Do you use animal manure (Cow Dung and Cow Urine) on your land?

Yes ☐
No ☐

15. Do you feel there is a difference between Cow Urine and Human Urine?

Yes ☐
No ☐

Comment (*Please note any remarks or comments to this question*)

____

____

____

16. Do you know anyone who used or uses Human Urine on his/her land as fertiliser?
Neighbours? Friends and Family? Ancestors maybe?

Yes ☐
No ☐

Comment (*Please note any remarks or comments to this question*)

____

____

____

17. How would you feel if…………..

17.1. Your Neighbour started using Human Urine as fertiliser on his/her farm?

____

____

17.2. Someone you know started using Human Urine as fertiliser on his/her farm?

____

____

____

18. Do you think people in the Market Place (*Sabji Mandi*) will buy food produced on a farm that uses Human Urine as fertiliser?

Yes ☐
No ☐
I can't say ☐
Comment____

____

____

19. Do <u>YOU</u> think Human Urine can be used as a fertiliser?

Yes ☐
No ☐
I can't say ☐
Comments (*Please note any reactions or comments given in response to this question*)

____

____

____

If answer to Question 19 is <u>YES</u>, Go to Que <u>20</u> AND <u>20.1</u> (4 statements);
If answer to Question 19 is <u>NO</u>, Go to Que <u>20.2</u> (7 statements);

20. Do <u>YOU</u> think it would be a good idea to use Human Urine to fertiliser <u>YOUR</u> crops?

Very Good Idea ☐
Good Idea ☐
Bad Idea ☐
No Opinion ☐
Comments (*Please note why the farmer thinks it is good or bad, or why he does not have opinion*)

____

____

____

____

20.1. If GOOD idea, please ask these questions,

1. Human urine is good for my soil; Yes ☐ or No ☐
2. Human urine will increase my crop productivity; Yes ☐ or No ☐
3. Human urine is good if it is sanitised and used safely; Yes ☐ or No ☐
4. If I use Human Urine, I have to buy less fertiliser from market; Yes ☐ or No ☐

20.2. If BAD idea, please ask these questions:

1. Crops can die if fertilised with urine; Yes ☐ or No ☐
2. The taste of crops and vegetables will change if I use urine; Yes ☐ or No ☐
3. I use animal manure, so I don't need human urine; Yes ☐ or No ☐
4. There are health risks associated with urine, so I will not use it; Yes ☐ or No ☐
5. The smell of urine is a hindrance; Yes ☐ or No ☐
6. People will mock me or make fun of me; Yes ☐ or No ☐
7. I will never use human urine for my crops; Yes ☐ or No ☐

21. If Dry Fertiliser (urea) is safely manufactured using human urine would you buy and use it?

Yes, Would Buy ☐
Yes, Would Buy if it is Cheaper than what I pay for fertilisers now ☐
Yes, Would Buy if Cost is similar to what I pay for fertilisers now ☐
No, No Need ☐
No, Bad Idea ☐
No Opinion ☐

22. Would you consider using Human Excreta (Faeces) on your land as fertiliser?

Yes, Very Good Idea ☐
Yes, Good Idea ☐
No, Bad Idea ☐
No Opinion ☐
Comments (*Please note why the farmer thinks it is good or bad, or why he does not have opinion*)

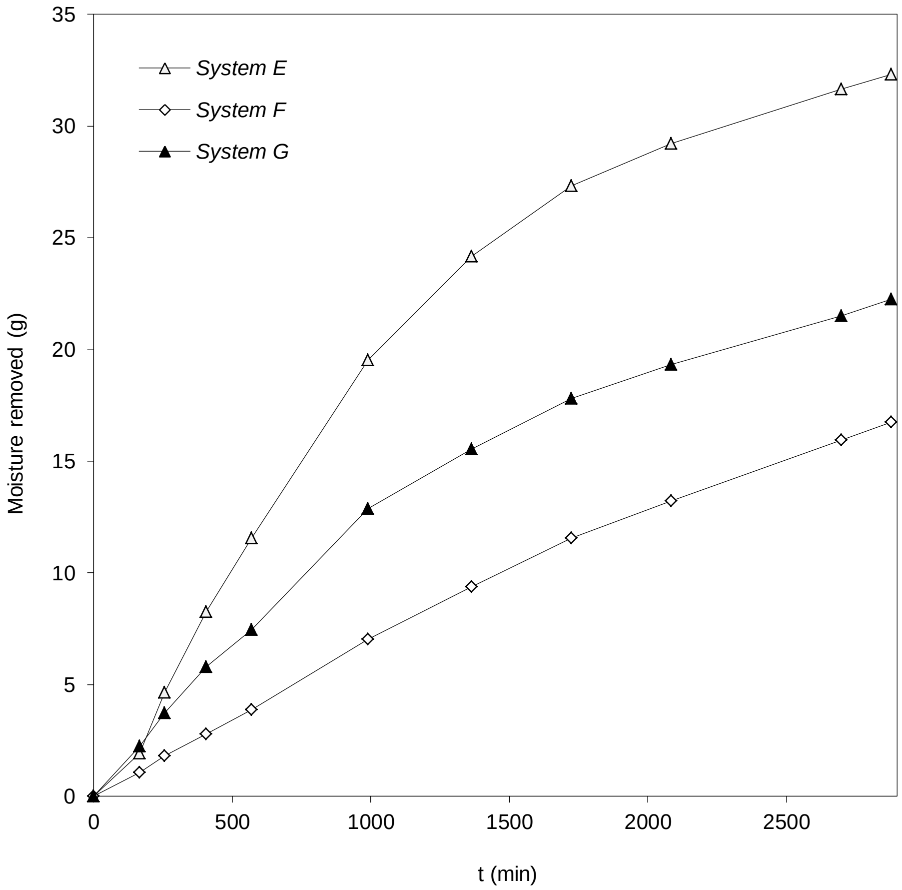
____

____

____

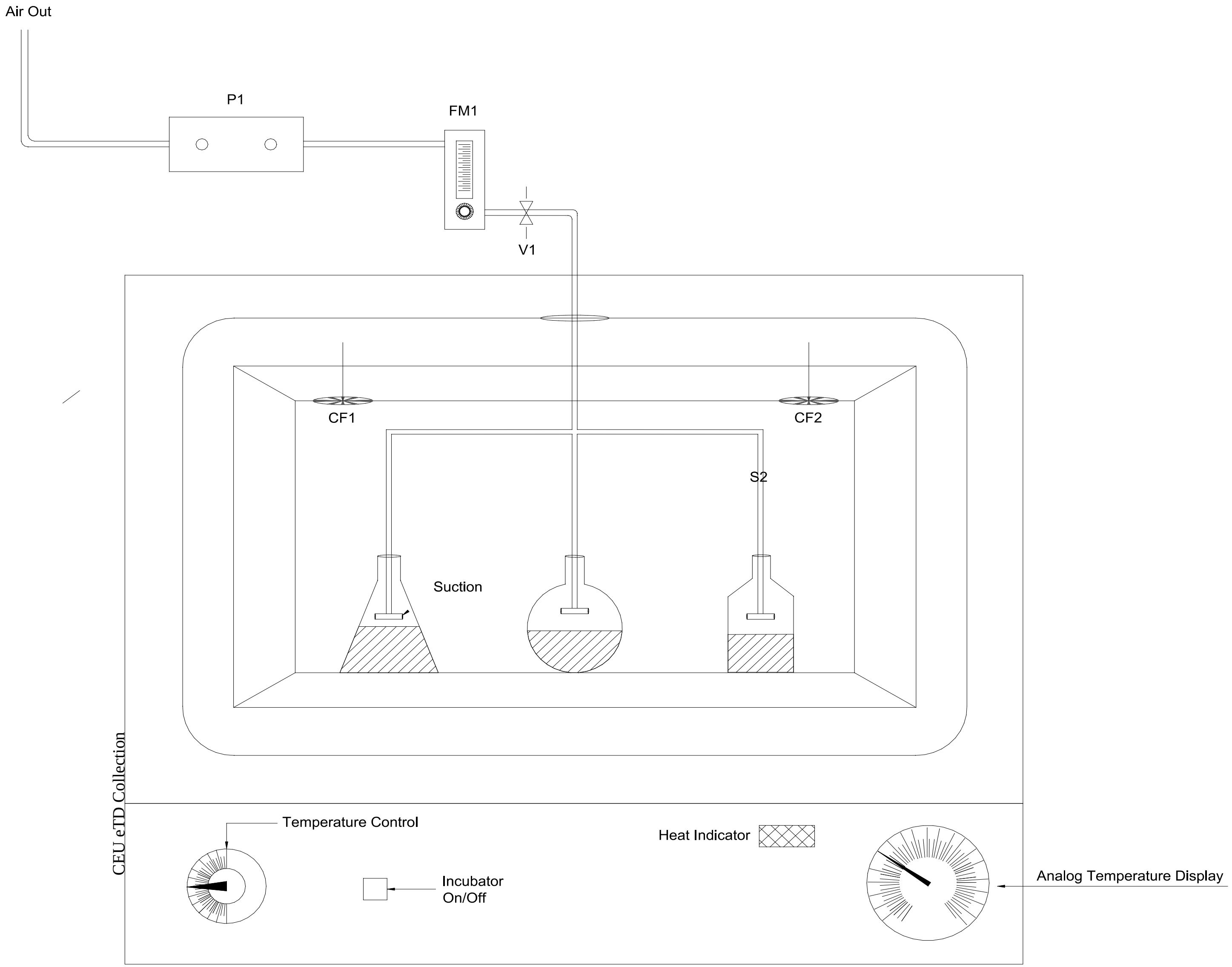
____

Appendix AX8: Results for urine drying in *Systems* E to G				
Property	*System E*	*System F*	*System G*	Units
Volume of Urine Evap	0.032	0.016	0.022	L
Total Area	0.013	0.006	0.006	m^2
Total time	2880	2880	2880	min
Rate of Evap	1.23	1.45	1.71	$L.day^{-1}.m^{-2}$
Outlet Air T	39.5	39.5	39.5	°C
Saturation Vapour Density	47.42	47.42	47.42	$g.m^{-3}$
Actual Humidity	3.741	1.939	2.576	$g.water.m^{-3}$ air
Relative Humidity	7.888	4.088	5.433	%



Appendix AX 9: Variation of moisture content in the ash with time for *Systems* E–G

Appendix AX 10: Schematic diagram for the setup used in urine drying for *Systems* E–G



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